PB-245 772

HAZARDS OF MERCURY

Department of Health, Education, and Welfare
Washington, D. C.

November 1970

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

Hg Mercury

282024

PB 245 772

HAZARDS OF MERCURY

Special Report to the Secretary's Pesticide Advisory Committee,
Department of Health, Education, and Welfare

Study Group on Mercury Hazards

Norton Nelson, Ph.D., Chairman

Theodore C. Byerly, Ph.D.

Albert C. Kolbye, Jr., M.D., J.D.

Leonard T. Kurland, M.D., Dr. P.H.

Raymond E. Shapiro, Ph.D.

Samuel T. Shibko, Ph.D.

William H. Stickel, M.A.

Jack E. Thompson, D.Sc.

Lowell A. Van Den Berg, M.Sc.

Alfred Weissler, Ph.D.

November 1970

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. Department of Commerce
Springfield, VA. 22151

STUDY GROUP ON MERCURY HAZARDS

List of Members

Chairman and Member Secretary's Pesticide Advisory Committee

Norton Nelson, Ph.D.
Director, Institute of Environmental Medicine
New York University
550 First Avenue
New York, New York 10016

Consultant to Secretary's Pesticide Advisory Committee

Leonard T. Kurland, M.D., Dr. P.H.
Chairman, Department of Medical Statistics,
Epidemiology and Population Genetics,
Mayo Clinic; and
Professor of Epidemiology, Mayo Graduate
School of Medicine
200 First Street, S. W.
Rochester, Minnesota 55901

From Food and Drug Administration

Albert C. Kolbye, Jr., M.D., J.D.
Deputy Director
Bureau of Foods and Pesticides, BF-2
in charge of the Bureau Overview of Mercury
and Fish Program
Food and Drug Administration
200 C Street, S. W.
Washington, D. C. 20204

Raymond E. Shapiro, Ph.D.
Office Assistant Director for Scientific Coordination
Bureau of Foods and Pesticides, BF-5

Alfred Weissler, Ph.D.
Acting Director, Division of Colors and Cosmetics
Office of Foods and Nutritional Sciences
Bureau of Foods and Pesticides, BF-160

Samuel I. Shibko, Ph.D.
Division of Toxicology
Office of Foods and Nutritional Sciences
Bureau of Foods and Pesticides, BF-148
Toxicological Aspects of Mercury and Fish Program

From the Department of Interior

William H. Stickel, M.A.
Research Biologist
Patuxent Wildlife Research Center
Route 2
Laurel, Maryland 20810

From the Federal Water Quality Administration

Lowell A. Van Den Berg, M.Sc.
Assistant to Director
National Field Investigations Center
Federal Water Quality Administration
Department of Interior
5555 Ridge Avenue
Cincinnati, Ohio 45213

From the National Air Pollution Control Administration

Jack E. Thompson, D. Sc.
Assistant Director
Bureau Criteria and Standards
National Air Pollution Control Administration
411 West Chapel Hill Street
Durham, North Carolina 27701

From the Department of Agriculture

Theodore C. Byerly, Ph.D.
Assistant Director
Science and Education
Office of the Secretary
U.S. Department of Agriculture
Washington, D. C. 20250

TABLE OF CONTENTS

	Page no.
Introduction And Summary of Conclusions and Recommendations	1
Chapter 1 Medical Implications of Ingestion of Mercury	8
Chapter 2 Microbial Transformation of Mercury	25
Chapter 3 Sources, Distribution, and Control	29
Chapter 4 Ecologic Effects of Methylmercury Contamination	37
Chapter 5 Farming-Food-Forestry	48
Chapter 6 Airborne Mercury	61
Chapter 7 Analytical Methods	66
Appendix A (List of Persons Consulted)	75
Appendix B (Tabular Data on Production and Usage of Mercury)	85
Appendix C (Units for Expressing Concentration of Mercury)	87
References	88

INDEX OF TABLES

		Page No.
Table 1.	Mercury Content of Blood of Mothers and Newborn Children (from from data of Tejning 1970b)	12
Table 1A.	Content of Mercury (Hg) in Blood and Hair of Swedish Individuals	21
Table2.	Mercurial Discharge from Chlor-Alkali Plants in Sweden	30
Table 3.	Mercury in Foods	51
Table 4.	Mercury Residues in Grain & Fruit Untreated & Treated with Phenylmercury Foliar Spray	52
Table 5.	Methylmercury in Relation to Total Mercury in Some Animal Products	53
Table 6.	Total Mercury Content of Certain Scandinavian Animal Food Products	55
Table 7.	Tolerances of Pesticide Residues in Foods	58
Table 8.	Annual Mercury Budget	64
Table 9.	Radioactive Isotopes of Mercury and Their Respective Half-Lives	68

INDEX OF FIGURES

Figure 1.	Conversion of inorganic mercury and some mercury-containing compounds to methylmercury	26
Figure 2.	Mercury cycle in the environment	63

Introduction

and

Summary of Conclusions and Recommendations*

The study group submitting this report was assembled to secure further information on the hazards of mercury from the extensive knowledge and experience developed in Sweden and Finland.

The problem of mercury contamination in the United States is potentially grave, but only recently have efforts been made to define its magnitude. Since the problem has been under intensive study for some years in Sweden and Finland where the patterns of usage of mercury are similar to those in the United States, the knowledge and experience gained in those countries could be extremely useful to us.

The HEW Secretary's Pesticide Advisory Committee, and the FDA jointly concluded that a visit to Sweden and Finland would be desirable. As the planning progressed, it became evident that, to make maximal use of such a visit, it would be desirable to bring in other Federal agencies having responsibilities in this area. On this basis, representatives were designated from the Federal Water Quality Administration, the Bureau of Sport Fisheries and Wildlife (both from the Department of the Interior), the Department of Agriculture, and the National Air Pollution Control Administration. Because population studies are integral parts of pollution research and since alkyl mercury compounds derange the nervous system, an expert in epidemiology and neurology was added to the group.

The study group, consisting of 10 individuals, spent the week of August 16 in Sweden in a series of intensive meetings with physicians, scientists, engineers, and public officials who have been actively working on the mercury problem in that country.** Three days were spent in similar discussion with experts in Finland the following week. The present report summarizes the findings of the study group and sets forth recommendations relating to major steps which should be taken in this country to define and correct the problem of mercury pollution.

Although the toxic qualities of metallic mercury and methylmercury have long been recognized, the present situation stems from the extensive increase in the industrial and agricultural uses of mercury in recent decades. The current problem can be divided into two broad parts: one relates to the toxicity of unmodified mercury pesticides and the other to accumulations in aquatic systems of alkylated mercury from a variety

---

* Prepared by Norton Nelson

** The Swedish Commission on Evaluating the Toxicity of Mercury in Fish is just now completing an extensive report based on a thorough review of the problem. The present study group is most grateful to the members of the Commission for their willingness to make available the information which was developed in their review and to discuss their findings with us. The study group is also deeply indebted to the Commission's Chairman, Dr. Lars Friberg, of the Karolinska Institute, for his helpful planning of the agenda of the study group. Similarly the study group is most grateful to Dr. Leo Noro, Director General of the Finnish Medical Board for arranging the agenda in Finland.

of sources. The aquatic problem concerns, almost wholly, a mechanism whereby mercury in the bottom muds of contaminated waterways is converted into methylmercury which is far more toxic to the brain on a chronic basis than is inorganic mercury. The methylmercury is concentrated in fish and shellfish, partly through contamination of their food and partly through its presence in the water. Thus, the level of mercury is several thousand times greater than that in the water.

When contaminated fish are ingested by man, methylmercury is assimilated. The relative ease with which methylmercury passes the "blood-brain barrier" accounts for the severe neurologic manifestations, and even death, which may follow the accumulation of small amounts of this compound. The slow rate of elimination of methylmercury, which has been demonstrated in both fish and man, potentiates this effect.

The syndrome of methylmercury poisoning in man through the consumption of contaminated fish and shellfish has now come to be known as "Minamata disease" because of its discovery in the villages surrounding Minamata Bay in Kumamoto prefecture, Japan. The clinical picture of the disease, first observed in 1953, includes progressive blindness, deafness, incoordination, and intellectual deterioration.

Two outbreaks have been identified in Japan, one in Minamata where 121 cases with 46 deaths were identified up to 1970 and another in the riverside villages of the Agano River in Niigata prefecture where 47 cases with 6 deaths were observed through 1970. Of the 121 cases in Minamata, 23 were cases of a cerebral palsy-like disease of infants who had not consumed contaminated fish; however, their mothers had done so but were apparently free of symptoms of the disease: one fetal case observed in Niigata was considered mercury related (Takeuchi, 1970).

The staff of the Kumamoto University, in a series of carefully planned investigations, first identified the causative factor of Minamata disease as heavy consumption of fish contaminated with an organic form of mercury, later identified as methylmercury. Similar findings were made by the staff of the University of Niigata in the Niigata City and Agano River outbreak. These studies established the general nature of the disease, related it to the level of intake of fish, and defined the associated burdens of mercury in several tissues of the victims of the disease. Subsequently, and in relationship to the fetal cases just mentioned, it has been shown in Sweden that, in contrast to inorganic mercury which passes the placenta poorly, methylmercury is concentrated in fetal red blood cells to values about 30% higher than in maternal red blood cells.

The sources of mercury contamination in Minamata Bay and Niigata proved to be the discharges from plants using mercury catalysts in the manufacture of vinyl chloride and acetaldehyde. It was reported that methylmercury was preformed in the effluent of these factories.

(5) This page from Nov. '70 draft

Subsequently, in Sweden, it was also found that inorganic mercury is converted, by microbial systems in the bottom muds, to methylmercury which is then concentrated as previously described. Thus, the hazard to man was associated with his eating fish and shellfish and not simply on the presence of methylmercury in the water.

From the human health standpoint, central issues are the level of contamination of fish (and other foods) and the extent of their consumption. The mercury contamination in bottom sediments of waterways constitutes a depot which, through the methylating process, represents a potential continuing source of methylmercury. The problem of decontamination is thus both urgent and difficult. All discharges of inorganic and organic mercury can presumably contribute to this depot.

In addition to this subtle and newly discovered mechanism of the conversion of inorganic mercury to methylmercury, there is the more straightforward problem of the toxicity for wildlife, domestic animals, and human beings of the mercurial pesticides used in agriculture. Seed treatment came into extensive use after World War II. In addition to episodes of acute poisoning occasioned by the accidental eating of treated seeds or of animals fed on such seeds, there has been such widespread mercury contamination reaching toxic and, indeed, lethal levels, particularly for certain birds. Water contamination has come largely from loss in such industries as chlorine and alkali production and from the use of phenyl mercuric acetate as a standard for the control of slime in the manufacture of paper pulp.

The visit of the study group to Sweden and Finland was most fruitful. Part of the product of the visit is expressed in the following pages; a very important part does not appear in writing but resides in gains to each member of the study group. In an improved understanding of many technical facets of the mercury problem and, most importantly, in the development of a solid sense of priorities. These come about through direct contact with experts in the countries visited, who have been engaged in this problem for the last 5 years. The personal gains, improved by the collective interchange between representatives of the various federal units concerned with the mercury problem, are immediately applicable to an accelerated and more efficient attack on this problem.

The report should serve as an assessment of hazards of mercury as of mid-1970. It contains many specific recommendations aimed at better understanding and early solution of the mercury problem in the United States. The major objectives are briefly summarized in the following section.

Summary of Conclusions and Recommendations*

The levels of mercury contamination found in fresh-water fish in Sweden and Finland are similar to those found in such fish in the United States. On the other hand, fish consumption in this country is regarded as generally somewhat less than in the region of Scandinavia. Medical examinations of heavy eaters of contaminated fish have not revealed conclusive evidence of mercury-related disease in either Sweden or Finland. Nevertheless, the body burdens of mercury of some of those having the heaviest intake of fish in both of those countries were as high as the lower levels reported in persons with methylmercury poisoning in Japan.

The major conclusion derived from these and other findings was that it seems unlikely that we will find overt mercury poisoning from the consumption of fish or other food products, as normally marketed, in this country. This is not to say that there may not be a few individuals, who because of high consumption of contaminated fish may have signs of mercury poisoning or suffer possible subclinical effects, including delayed neurologic or intellectual damage. Also, possibly infants or children may have impaired development. As yet, no systematic studies have been undertaken, even in the known areas of human exposure in Sweden and Japan, to identify such subclinical effects.

Although we appear to be on safe ground, it is urgent (1) to determine whether subtle health effects are present and (2) to use all possible means to reduce exposure to mercury immediately.

The recommendations of the study group are summarized here. The individual chapters should be consulted for detailed recommendations.

1. Current Regulations.--The study group has concluded on the basis of their examination of the experience in Sweden and Finland that the interim FDA guide line of 0.5 ppm in fish is, for the present, a sound basis for the protection of public health. However, the margin of safety may not be large, and residual uncertainties remain in regard to possible hazard where large amounts of contaminated fish are eaten. Resolution of these questions will require further study. Recommendations aimed at clarifying these questions are outlined in the attached report.

2. Human Exposure.--The extent of exposure of the general population appears to be chiefly through fish and possibly other foods and not directly through water or air. The normal and extreme patterns of food consumption, particularly of fish, need thorough documentation. This should be undertaken as a series of cross-sectional studies of patterns of food intake in relation to relevant personal (age and sex), regional, ethnic, and cultural patterns.

---

* The order of mentioning recommendations here and in subsequent chapters does not necessarily denote priorities.

3. Effects on Health.--In respect to the health hazard, it will be essential to undertake population studies (1) to relate the body burden of mercury (level of mercury in the tissues) to the ingestion of mercury, particularly from fish, (2) to develop and to apply more sensitive diagnostic techniques to identify possible subclinical and late mercury toxicity, (3) to undertake medical studies of a prospective nature (studies of exposed populations who currently demonstrate no obvious ill effects) in this country and possibly collaborative studies elsewhere with respect to late consequences of exposure to mercury, (4) to assess the potential effects from prenatal and postnatal exposures to mercury, since these are of the highest priority in respect to possible undetected injury, (5) to determine the body burden of mercury at different occupational patterns of exposure, and (6) to assess the possible synergistic interaction of mercury with other potentially hazardous residues in fish.

4. Ecologic Effects.--The effects of mercury on the ecology of birds and other wildlife served to alert Sweden to the problem of mercurial contamination. Such effects are real and pervasive. In view of the near certainty that mercury will be in our environment, especially in the fresh-water environment, for some time to come, these effects, which are still poorly identified and understood, need considerably more study. For specific recommendations, see Chapter 4.

5. Control.--All controllable sources of mercury contamination should be either eliminated or maximally reduced. Thus, (1) the use of all alkylmercury pesticides should be terminated and all other mercurial pesticides should be severely restricted to usage on a basis of demonstrated need only. Safe substitutes should be sought for those remaining in use and not now possible to eliminate. (2) Further safeguards should be developed for the manufacture, packaging, distribution, and field use of seed treated with organic mercurials and for the disposal of unused treated seed and its containers to avoid mercurial poisoning through accidents or misuse of such materials. (3) All industrial users of mercury, particularly those operating chlorine and alkali production plants and those using mercury catalysts, should be required to reduce their discharges of mercury into the environment to levels approximating background levels. (4) Other sources of mercury contamination or exposure--for example, discarded electrical equipment, chemicals, paints, cosmetics, pharmaceuticals, sewage, and fossil fuels--must be identified and brought under control. The urgency of this is emphasized by the circumstance that, although mercury in any form is hazardous, all forms of mercury have the potential to be converted to the highly toxic form of methylmercury.

6. Analysis.--Analytical reliability with respect to both amounts and forms of mercury are essential for assessment and control. It appears

that--with the rapid improvement in analytical procedures in the last few years--methods are now available to meet most current requirements. The study group recommends (1) that a system of validation of analytical equipment, methods, and results be developed, (2) that information on the most suitable procedures be immediately disseminated, and (3) that further refinement and improvement in techniques be undertaken as spelled out in the accompanying report. These procedures should take into account the growing need to analyze for other heavy metals also.

7. Distribution and Transport.--The contribution of natural (geologic) deposits of mercury to the current problem is poorly understood and needs clarification. It has been suggested that the atmosphere and oceans may be major and important routes for the global transport of mercury and this hypothesis needs detailed examination. The movement of mercury from natural and man-made sources into waterways is still not well defined and requires better specification. Similarly, the roles of microbial flora, water pH, sunlight, and so on in the transformation of mercury in waterways is poorly understood and their clarification could play a decisive role in control.

8. Decontamination.--It appears probable that, even with the complete elimination of new discharges of mercury, existing deposits in sediments of waterways will continue to yield the highly toxic methylmercury to waters for decades to come. Interruption of this methylation or decontamination of existing deposits is thus of the utmost urgency. An intensive program aimed at the decontamination of existing deposits should be initiated immediately. This will involve an extensive series of studies, ranging from the type performed in the laboratory to large-scale pilot experiments on existing contaminated waterways. Sweden has launched an extensive program aimed at decontamination. This work should be followed closely; however, we cannot depend on Sweden to provide answers for the United States; the urgency, the magnitude of the problem, and special circumstances in this country, all require that a major independent effort be undertaken.

9. Collaboration and Communication.--The interplay of the several talents and responsibilities brought together in the study group was extremely useful. Consideration should be given to the continuation of this group, or a similar one, on a regular consultative basis for purposes of program coordination until such time as the hazards of mercury have been brought under control.

10. Other Hazards.--This mercury experience points up the need to review meticulously other toxicants in the environment, such as other heavy metals, for possible dangers.

The full report which follows is, in every sense, a collective effort of the study group. Although each section was written primarily by an individual or small group of persons, all sections reflect benefits from joint discussion with other members of the group and in many instances direct contributions. The issues have been dealt with under the following headings: (1) Medical Implications of Ingestion of Mercury, (2) Microbial Transformation of Mercury, (3) Sources, Distribution, and Control, (4) Ecologic Effects of Methylmercury Contamination, (5) Farming-Food-Forestry, (6) Airborne Mercury, and (7) Chemical Analyses.

A list of persons consulted is given in Appendix A. Some tabular data on the production and usage of mercury are assembled in Appendix B. Appendix C compares units used for the expression of mercury concentration.

CHAPTER 1

MEDICAL IMPLICATIONS OF INGESTION OF MERCURY*

Background

Although metallic mercury and its inorganic, alkoxyalkyl, and aryl compounds can have detrimental effects on man and other animals, it has become clear that methylmercury through its propensity for the nervous system, its long retention within the body, and its effect on developing tissue poses a particularly serious problem. As will be shown, methylmercury and other alkyl-mercury compounds can have a devastating effect on the integrity of the nervous system.

It appears that mercury enters the food chain as methylmercury after conversion by microorganisms in the silt of waterways (see Chapter 2 for details). Studies by Swedish investigators (Westöö and Rydalv 1969) confirm the earlier evidence that methylmercury is also present in high concentrations in contaminated fish from Japan, and there is little doubt that the mercury in the Minamata Bay and Niigata incidents was in the form of methylmercury.

Most of the mercury compounds used in agriculture and industry(such as alkoxyalkyls and aryls) can be grouped, on the basis of their effects on man, with inorganic mercury to which the former compounds usually are metabolized. In general, these substances are particularly known for their effects on the kidney and liver.

Until recently it was thought that all methyl- and other alkyl-mercury compounds in the environment were man-made--directly, in laboratory or industrial production, or indirectly, in the inadvertent and undesirable formation of waste products during the production of vinyl chloride and acetaldehyde with mercuric chloride catalysts. The recognition of the natural methylation of many forms of mercury suggests that it is this conversion mechanism which may be contributing to the high levels of methyl-mercury in fish in polluted waters.

Human Response to Alkyl Mercury

Greco (1930) opened his description on the effects of alkyl mercury as follows: "It can be said that the history of the alkyl compounds began with a tragedy. In 1865 two young chemists, while working on the preparation of diethyl mercury, inhaled the vapours and were poisoned by the very volatile product. One of them died in 11 days, and the other died after a year during which he had been blind, deaf and almost completely demented."

---

*Prepared by L.T. Kurland, S.I. Shibko, A. Kolbye, and R. Shapiro

Outbreaks of methyl- and other alkyl-mercury poisoning have been recognized, affected persons being industrial workers and farmers producing or otherwise handling such agents. The effects of alkyl mercury as an industrial intoxicant in a seed-treatment plant were described in detail in a report of four cases by Hunter et al (1940). The clinical features included paresthesias (numbness and tingling) of the extremities, mouth and lips; concentric constriction of the visual fields which might progress to blindness; loss of hearing; unsteadiness of gait; loss of coordination; reflex changes, including extensor plantar responses; and, in more severe cases, loss of ability to speak and progressive intellectual deterioration. The patient in one of the cases described by Hunter et al (1940) was to provide a critical lead in the recognition of the role of organic mercury in the Minamata Bay catastrophe. This patient died years later of pneumonia. Autopsy reportedly (Hunter and Russell 1954) revealed the following main pathologic features: (1) cerebellar cortical atrophy, selectively involving the granular-cell layer of the neocerebellum, and (2) cortical atrophy of the area striata (calcarine fissure-visual cortical area of the occipital lobe).

The human consumption of grain treated for seed purposes has led to several outbreaks of mercury poisoning in which more than 450 persons became ill and many died (Guatemala, Iraq, and Pakistan) (Ordonez et al 1966, Jalili and Abbasi 1961 and Haq 1963). In the United States, in 1969, seven persons in a New Mexico family consumed pork from animals which had been fed seed grain coated with methylmercury dicyanodiamide; three children in the family evidenced severe brain damage of the type seen in Minamata disease. The pork contained 25 ppm of mercury (the grain 32 ppm). (Hinman 1970 and Likosky et al 1970)

Other cases of mercury intoxication after exposure to methylmercury and alkoxyalkyl-mercury compounds used in seed treatment were reviewed in earlier reports (Kurland et al 1960). A case similar to that of Hunter and Russell (1954) recently was reported by Schmidt and Harzmann (1970). The patient in this case had been exposed to the dust of an ethylmercury fungicide and had had a syndrome similar to "Minamata" disease; he died 18 years later. Central nervous system pathology predominantly involved the visual cortex of the cerebrum, similar to that described by Hunter and Russell (1954).

Minamata Disease.--"Minamata disease" or methylmercury poisoning due to ingestion of contaminated fish, occurred in a village near the Minamata Bay, Japan, from 1953 through the 1960s, and affected at least 121 children and adults, of whom 46 died. Among the 121 patients were 23 infants and children who had a cerebral palsy-like disease from 1954 to 1959. This was referred to as congenital (or fetal) Minamata disease Harada 1968 and Takeuchi 1968). In 1964 and 1965, the disease again was reported--this time among 47 persons, 6 of whom died, in Niigata, Japan.

The clinical features in children and adults included paresthesias (numbness and tingling), progressive incoordination, loss of vision and hearing, and intellectual deterioration. These features, as well as the pathologic findings, were similar to those referred to above in the cases described by Hunter et al (1940), and Hunter and Russell (1954). The neurologic and neuropathologic findings and their frequency in clinical cases of varying severity affecting patients of various ages are presented in detail in published reports (Kutsuna 1965 and Tsubaki 1967). The brain damage largely had been accomplished by the time the diagnosis was made and, although chelating agents increased the rate of excretion of mercury in the urine, their administration was clinically ineffectual. Therefore, since there is no effective therapy for overt methylmercury poisoning, prevention is the means of control to be emphasized. Because of the delay in recognition of these outbreaks in Japan, it is likely that the number of persons who truly were affected was appreciably greater than reported. Furthermore, relatively early cases with less neurologic deterioration were often recognized in Niigata, suggesting that many mild cases were missed in Minamata. This is supported by the recent report of Takeuchi (1970) that a medical practitioner in one village near Minamata Bay who had had tremor and some intellectual symptoms had clearcut evidence of Minamata disease at autopsy. It would appear that compensatory mechanisms of the nervous system can delay clinical recognition of the disease even when the patient has partial brain damage.

The works of Irukayama (1965), Takeuchi (1968, 1970), and others, have established the etiologic role of methylmercury in Minamata disease (Study Group of Minamata Disease, 1968).

The contribution of Swedish investigators (Westöö and Rydalv 1969) is that the mercury in tissues of fish from the lakes in Sweden, as well as Japan, exists almost entirely as methylmercury. The work of Swedish scientists and of Tillander and his co-workers (1968) in Helsinki indicates that methylmercury was the active agent of Minamata disease and that this agent has the same toxic effect whether derived from contaminated fish in the lakes of Sweden and Finland or given in the pure chemical form.

Prenatal and Postnatal Exposure

Occurrence of Mercury in Milk.--The occurrence of mercury in mammary glands (Berlin and Ullberg 1963) would confirm reports of mercury in mother's milk (Perrin 1911) and the reported changes in the brains of baby rats nursed by mothers with organic mercury poisoning (Deshimaru 1969).

Also, Bakulina (1968) reported both transplacental passage of ethylmercury and passage through mother's milk.

Placental Transfer.--Methylmercury crosses the placental "barrier" and ever achieves a 30% higher concentration in fetal red blood cells than in maternal red blood cells (Tejning 1970c). / The fetal plasma, however, has a lower concentration than does maternal plasma. The difference, therefore, may be due to differences in the binding of methylmercury by maternal and fetal hemoglobins. The toxicologic significance of these findings with respect to methylmercury in fetal brain, is now unknown. Methylmercury is more readily transferred across the placental barrier than is mercuric chloride or phenyl mercuric acetate (Suzuki et al 1967).

Congenital (Fetal) Disease.--Twenty-three (6%) of 359 children born in the villages near Minamata Bay from 1954 through 1959 were affected with a cerebral palsy-like disease. The disease varied in severity, some children having mild-to-moderate spasticity and ataxia, and others having severe intellectual retardation, seizures, and evidence of more-generalized brain damage.

The method of case ascertainment resulting in the rate of 6% is not known, but the rate is significantly higher than the 0.1% to 0.6% reported in other populations (Harada 1968).

Several features are particularly noteworthy in these cases: (1) The affected children had not eaten contaminated fish or shellfish. (2) The mothers apparently were not affected. (3) Clinical symptoms were more difficult to elicit and more varied than in cases of Minamata disease in adults and children. The possibility exists that the intensive search for cases merely disclosed coincidental cerebral palsy in the population. However, this is highly unlikely, since the incidence is quite excessive, the infants studied had abnormal levels of mercury in their hair, and those dying had high levels of mercury in brain, liver, and kidney--in the ratio of about 1:7:5 (approximating that found in the adult disease). Furthermore, the two autopsied cases showed depletion of granular cells in the cerebellum and cerebral cortical damage (but not selective for the visual cortex). They also showed evidence of hypoplasia and disarrangement and malformation of nerve cells; and, although these changes also may be seen in other forms of cerebral palsy, the burden of evidence favors methylmercury toxicity during fetal development.

Since the brains of these infants were still developing after birth and since severe exposure to mercury also could have been through mother's milk, the term congenital (fetal) attached to these cases by Harada (1968) and Takeuchi (1965) may seem inappropriate. However, on critical review of the autopsied cases at least, some prenatal effect of methylmercury seems likely. Until the issue is further evaluated, it might be best to refer to such cases as infantile Minamata disease. However, Harada maintains that the distribution of brain lesions in these cases is not identical with that in cases where affected patients presumably have been exposed as young children. It would be helpful if comparisons with non-

Table 1

Mercury Content of Blood of Mothers and Newborn Children (From data of Tejning 1970b)

Persons Studied	Group	Mercury Content, µg/gm RBC av	RBC SE	Plasma av	Plasma SE
14	Children	.0115 (0.006-0.021)+	0.0018	0.0019 (0.0011-0.003)+	0.00017
14	Mothers	.0086 (0.004-0.015)+	0.0008	0.0025 (0.0013-0.0045)+	0.00025
Mean Ratio Child/Mother		1.33		0.77	

+ Range

Minamata retarded infants had been made by the same investigative team. However, as indicated, initial review indicates that an effect on the fetus is a reasonable conclusion.

Metabolism, Distribution, and Excretion of Methylmercury in Man

Available data are based on distribution and excretion studies following oral administration of single doses of methylmercury labeled with mercury-203 (^{203}Hg) to human volunteers. There was a rapid uptake of labelled methylmercury by erythrocytes. The main activity (approximately 50%) was localized in the liver, whereas the head accounted for 10% of the activity. Mercury was excreted principally in the feces, with lesser amounts being excreted in the urine. Fecal excretion amounted to about 3% to 4% for the first few days, and then about 1% per day. Only about 0.1% per day was lost in the urine. Although methylmercury is highly concentrated in the hair and epidermis, these tissues have relatively small excretory roles in relation to the body burden. The biologic half life of methylmercury-203 as measured by total body measurement, was 70 to 74 days. From the results of this experiment, it was calculated that at equilibrium a weekly unit dose of methylmercury-203 would result in the whole-body burden being maintained at 15.2 units of mercury (Falk et al 1970).

Preliminary results of experiments in which burbot containing bound methylmercury-203 was fed to human beings were similar to those obtained when methylmercury-203 was fed as such. In this work, the plasma disappearance was more rapid than disappearances from the whole body--the half life in plasma being roughly 50 days compared to approximately 75 days for the whole body. Thus, the proportion of mercury in the blood drops with time; constituting about 5% initially, it drops to about 1% at 150 days (2 half lives for the whole body, and 3 half lives for blood) (Miettinen 1969).

The biologic half life of mercury in human beings also has been measured by determining changes in blood levels as individuals change from a diet of fresh water fish containing mercury residues to a diet of fish with a very low mercury content. The biologic half life observed was 69 to 70 days for mercury in red blood cells, and 76 to 83 days for mercury in plasma (Tejning 1967c).

Animal Studies

Animal studies that simulate human responses both in symptoms and metabolism, do not yet appear to be defined precisely. However, animal studies have contributed important information (1) on the metabolism of alkyl and aryl salts of mercury; (2) to the concept of a steady state between intake, distribution in tissues (body burden), and excretion of

methylmercury, (3) to the concept of cortical concentration of methylmercury in the brain, producing neurologic effects, and (4) for the investigation of potential mutagenic and teratogenic effects of mercurial compounds.

Absorption & Metabolism of Organic Mercury Compounds.--

Absorption. Inorganic mercury salts are less well absorbed than organic mercury salts. Studies by Fitzhugh, et al.(1950) have indicated that rats absorbed approximately 50% of dietary mercuric acetate (at dietary levels of [illegible] ppm). An estimate by Clarkson (1970), is that dietary absorption of mercuric chloride is approximately 2%. Phenyl- and methyl-mercury are absorbed unchanged. In the case of phenyl mercuric acetate, the intestinal absorption in rats is in the range of 50% to 90% (Fitzhugh et al 1950). For methylmercury, the available data (man and rat) indicate an intestinal absorption of more than 90% (Berglund and Berlin 1969).

Metabolism. From a toxicologic point of view, the most important differences between alkyl and aryl salts of mercury are the differences in the rates of removal from the tissues and in the amounts entering the brain and the fetus. The rates of metabolism of organic compounds of mercury to inorganic mercury, appear to be important factors in determining their tissue distribution and rates of excretion. Major differences in the metabolism of alkyl and aryl compounds have been clearly demonstrated in several studies. Phenyl mercuric acetate has been shown to be excreted by rats, unchanged, into the circulation from the intestine, presumably by metabolism in the liver and kidneys and excreted in the urine, largely as inorganic mercury. Intact phenyl mercuric acetate was only detectable for 96 hours. Less than 1% of the administered dose was excreted unchanged in the urine. In contrast, methylmercuric chloride administered to rats, intact ethyl mercuric chloride was detectable in liver and kidneys for 21 days. The excretion of ethylmercury was not as rapid as that observed with phenylmercuric acetate. There was appreciable urinary excretion of the unchanged compound. The total excretion of ethylmercury during the 7 days following administration was only 1/20th of that observed in the study with phenylmercuric acetate (Magos et al 1960, 1961). A comparison of the excretion patterns of rats fed either phenyl mercuric acetate or methylmercuric chloride showed that of the mercury from a single dose of phenylmercuric acetate, 87.4% was excreted in the feces and 12.6% in the urine within 7 days. Of the inorganic mercury was excreted in the urine (Ellis and Fang 1967). The differences in excretion patterns is related to the rapid metabolism of phenyl mercury to inorganic mercury.

Additional evidence that the metabolism of organic mercury compounds is an important factor in the excretion of mercury has been demonstrated

by Norseth (1969), who made a detailed study of the metabolism of methylmercury in rats. In this study, about 40% of the total mercury excreted was in the form of inorganic mercury (5% fecal and 5% to 20% urinary). Norseth showed that fecal mercury may be derived from a number of sources, including enterohepatic circulation, shedded intestinal epithelium, pancreatic secretion, and some secretion from the pylorus. A major source of inorganic mercury in the feces was the metabolism of protein-bound methylmercury within the lumen of the cecum. The mercury in the bile was shown to be chiefly in the form of methylmercury cysteine with lesser amounts as an inorganic form bound to protein. The cysteine complex was rapidly reabsorbed and was available for redistribution within the body; whereas, the inorganic mercury was absorbed poorly.

Another factor that may be important in controlling the rate of excretion of methylmercury is the rate of turnover of epithelial cells of the intestinal mucosa. Berglund and Berlin (1969) have pointed out that the turnover of these cells in rats is five times faster than that in man, and this correlates with the differences observed in rates of elimination of methylmercury in the two species.

1. Metabolism of Dimethyl Mercury.--Available information indicates that mercury may be methylated to either methylmercury or dimethyl mercury (Jensen and Jernelov 1969) (See later for distribution in the environment). The observations of Ostlund (1969) show that the two compounds behave very differently in the mammal. Studies with mice exposed to dimethyl mercury either through inhalation or injection, showed that most of the administered dose was rapidly exhaled as intact dimethyl mercury. Smaller amounts of the compound were metabolized to methylmercury which, in general, showed the same distribution in the body as did methylmercury administered as such.

These observations have significance, in respect to the "mercury problem", as follows: (1) They provide additional evidence that the causative agent of Minamata disease was a methylmercury compound (Uchida et al 1961a&b), and (2) they indicate that dimethyl mercury synthesized in the aquatic environment would not be accumulated by aquatic organisms, but would be available for further distribution in the biosphere.

Steady States.--Animal studies indicate a correlation between dose, body burden, and toxic effects of methylmercury.

Gage (1964) showed that rats receiving repeated subcutaneous doses of phenyl mercuric acetate reached a steady state by the end of the second week when excretion balanced intake. No significant amount of mercury was found in the brain. In contrast, rats receiving similar doses of methylmercury dicyanidiamide showed no indication of reaching a steady state after 6 weeks. Further, there was an accumulation of organic mercury in all tissues, particularly in the erythrocytes and the brain. In the case of alkyl mercury compounds in the rat, the level of mercury in the tissues has been shown to depend on the dose (Ulfvarson 1969). Although these short-term

studies with methylmercury failed to demonstrate a steady state, Berglund and Berlin (1969) showed that continuous administration of dietary methylmercury (1 to 5 ppm) to rats resulted in a steady state between body burden and excretion in about 6 months. At equilibrium the daily excretion corresponded to about 2% of the body burden (Berglund and Berlin 1969). There was a linear correlation between dose and body burden. The highest concentration of methylmercury in brain was 8 µg/gm* of brain tissue. (There were no effects on body weight or conditional behavior, and no pathologic or anatomic changes were observed.) (Berglund and Berlin 1969)

In similar studies in rats it was demonstrated that there was no increase in the concentration of mercury in the brain after 6 and 7 months of dietary administration, indicating that the brain reaches equilibrium with the rest of the body with respect to methylmercury (Ahlborg et al unpublished).

Concentrations of Mercury in the Brain and Neurologic Effects.--Suzuki et al (1967) proposed that a critical concentration of mercury in brain tissue is required to produce clinical effects. In a study to determine the threshold level in mice, after a single dose or multiple doses of methylmercury, it was found that death followed neurologic symptoms associated with concentrations of mercury of more than 30 µg/gm of brain, whereas survival was likely after neurologic symptoms associated with levels of 20 µg/gm brain (Suzuki et al 1967).

Exposure of cats to lethal levels of methylmercury in their food produced no apparent early clinical effects except anorexia which preceded, by a few days, the nearly precipitous onset of neurologic disorders. There were no clinical effects on the liver (although transaminase levels were not available) or kidneys (although occasional proteinuria was noted). Glycosuria has been described in cats (Pekkanen 1970) but this work needs repeating. The anorexia occurred a day or two before the onset of the ataxia and convulsions. By this time, it is apparently too late to counteract the neurologic effects of the methylmercury.

In cats with central nervous system (CNS) symptoms, having received in excess of 30 mg of methylmercury during periods of 30 days or more, brain concentrations in the order of 17 µg/gm were observed (Skerfving 1970). The average brain level associated with the death of cats was 30 µg/gm of brain (Takeuchi 1968).

In the few affected cats of Minamata, in which the ratio of the levels of methylmercury in brain, liver, kidney, and hair was determined, it was about 10:60:20:50 (Furland et al 1960); however, this analysis needs to be updated.

---

*Concentrations of mercury in various media have been reported in a variety of units; these are listed in Appendix C.

Rats dosed with methylmercury may have somewhat lower relative concentrations of mercury in brain than some other mammals ranging from about 10% to 60% of those in whole blood, the lower percentage being observed at higher doses (Gage 1964 and Ulfvarson 1969).

Human studies with isotope-labeled methylmercury indicated that about 10% was in the head, but this value presumably arose in part from the other tissues of the head, including the hair and is thus an upper estimate (Miettinen 1969).

Studies with mice showed that methylmercury is more readily transferred across the placental barrier than is mercuric chloride or phenyl mercuric acetate (Suzuki et al 1967). With respect to fetal effects, the following is of particular interest. A single dose of methylmercury was administered orally to rats 9 to 11 days pregnant. Nine days after a dose of 20 mg/kg of body weight, the content of mercury in the fetal brain was about four times that in the maternal brain, while after a dose of 2 mg/kg of body weight, the content of mercury in the fetal brain was about 70% of that in the maternal brain. Many biologic changes in the brain were noted after doses of both levels, but they differed in degree (Matsumoto et al 1967). These data raise the question of a possible difference in the fetal response to a very low level of exposure to mercury as compared to a high level of exposure.

Genetic and Teratogenic Effects of Organic Compounds of Mercury

Experimentally, in certain systems of plants and drosophila, organic compounds of mercury may produce genetic mutations and chromosomal aberrations, but such changes have not been demonstrated in test mammals.* C-mitosis[1] has been demonstrated in cells of Allium cepa roots exposed to concentrations of alkyl and phenyl mercury compounds at levels as low as 15×10^{-7}M (about 0.05 ppm). Alkoxyl compounds are less active and require levels as high as 30×10^{-7}M (about 0.7 ppm) for comparable effects. Although all the organic mercury compounds tested produce c-mitosis, the effects are not identical. Phenyl compounds give rise to distinctly more bridges and fragments than do other mercury compounds (Ranzi 1967). Methylmercury and phenylmercury are among the most active c-mitotic agents known, being 200 to 1,000 times more effective than colchicine.
As a result of the c-mitotic action, polyploid[2] as well as aneuploid[3]

*However, high levels of methylmercury have produced teratogenic effects in test animals.

[1]Abbreviated from colchicine-mitosis, c-mitosis refers to the characteristic appearance of chromosomes which have contracted more than is usual for mitotic metaphase and lie scattered within the nucleus.

[2]Polyploid: individual or cell with more than two full sets of homologous chromosomes.

[3]Aneuploid: number of chromosomes is more or less than the normal diploid number.

cells occur. The mercurial compounds cause c-mitotic tumors, and hook-like growths of the root are also observed--presumably representing incomplete tumorous action. Fahmy (1951) reported studies on the cytologic effects of organic mercury compounds, the results of which are in agreement with the data given by Ramel (1969). In addition, according to Fahmy (1951), inorganic mercury is about 200 times less effective than are organic mercury compounds in the production of c-mitosis.

In a study with Drosophila melanogaster, selected so that the c-mitotic effect could be traced on the gametes, treatment of female larvae and adults with methyl- or phenyl-mercury resulted in a significant increase in the number of exceptional daughter offspring (XXY) showing irregularities of meiotic chromosomal disjunction (Ramel 1967, Ramel and Magnusson 1969). Methoxy-mercuric chloride and inorganic mercury were not active even in higher concentrations in this system. It was also noted that other chromosomal effects and developmental disturbances (mutant gene and outstretched and bent wing) occurred.

The only reported experiments on mammals (inbred CBA mice) have failed to demonstrate dominant lethal mutations after administration of organic mercurial compounds (Ramel 1967).

However, although pregnant female CBA mice receiving single doses parenterally on the 10th day of gestation did not appear to be affected, they had a high frequency of resorbed litters and an increased percentage of dead fetuses (Ramel 1967).

The significance of the reported statistical increase in chromosomal breaks in blood cells of human consumers of large amounts of fish containing methylmercury remains to be clarified (Skerfving et al 1970).

In limited experiments with animals, teratogenic effects have been shown to follow administration of single high-level doses of methylmercury phosphate to pregnant rats on the 10th day of pregnancy. The treatment resulted in reduced body weight of offspring and a 31.6% incidence of cleft palate (Gharazawa 1968).

Distribution of Mercury in Blood.--The distribution of mercury in blood between red blood cells (RBC) and plasma depends on the type of mercury administered. For example, in the case of animals injected with inorganic mercury, the RBC mercuric level is approximately 25% of that of the total blood level (Berlin and Berglund 1969). Mercury in blood derived from aryl mercury compounds distributes evenly between the plasma and RBCs. In the case of methylmercury, at least 90% is bound to the RBCs. However, there appear to be some species differences respecting the fractions in plasma. For man, 10% is present in plasma; whereas, in rats, rabbits, and monkey, the respective levels are 4.5%, 10%, and 9% (Berglund and Berlin 1969). The mechanisms involved in this differential binding may be important in determining the amount of mercury available for

uptake by the brain and by the fetus--for example, the low levels of mercury in the brains of rats treated with methylmercury compared with those in the brains of animals of other species.

Dose-Response Considerations

The equilibrium rates between body burdens and rates of excretion and brain levels of mercury in animals and man and the relationships between levels of mercury in blood and hair are of importance in predicting possible toxic levels.

Brain Levels.--Methylmercury can cross the blood-brain barrier more readily than can other mercurial compounds--inorganic, phenyl, or methoxy; so the brain levels are much higher after administration of methylmercury than after corresponding doses of other agents. The level in the brain is slightly below the average total body level.

In fatal cases of Minamata disease, the ratio of mercury in brain, liver, and kidney varied, but generally was of the order of 10:40:50 (this ratio of about 5 to 1 for the level in liver or kidney versus that in brain contrasts with the distribution of inorganic mercury--usually about 20 to 30 times more in the liver and kidney than in the brain).

Information on levels of mercury in brain tissue of human beings has been obtained from individuals dying after acute exposure to methylmercury. Values ranging from 3 to 46 μg/gm of brain tissue have been reported (Berglund and Berlin 1969). The lowest value may have been measured by relatively insensitive methods and may only represent a fraction of the actual level of mercury in the brain. In the case of the Japanese patients, since it was likely that the source of mercury was removed from the diet on hospitalization, it is probable that the values reported are minimal values observed after an unspecified period of loss of mercury from brain tissue.

Takeuchi (1968) indicated that the neurones through the cerebral and cerebellar cortices may be affected, but that preferentially cells in the calcarine and precentral regions of the cerebrum and in the granular layer of the cerebellum are involved. The intensity of exposure and the age of the patient play some role in the distribution of lesions. Childhood cases (non-fetal) are said to show changes intermediate between the adult and "fetal" forms. Details of the distribution of brain lesions are presented by Takeuchi (1968).

Levels in Blood and Hair.--Limited data are available on this subject for individuals associated with the Minamata and Niigata incidents.

Most of the values were obtained weeks or months after onset of symptoms of affected persons, and the degree of exposure to mercury-contaminated fish often was not known definitely.

In Minamata, three patients had levels of mercury in the hair of 515, 565, and 763 μg/gm, respectively, and 15 members of their families had levels ranging from 15 to 412 μg/gm. Blood samples do not appear to have been obtained at the time of intoxication, but levels higher than 4 μg/ml of blood equivalent to 8 μg/gm in the erythrocytes have been reported (Berglund and Berlin 1969).

In the Niigata incident, it appears that the lowest blood level at which symptoms were observed were of the order of 0.2 μg/gm of blood and more than 200 μg/gm of hair. Again, we do not know the degree of exposure or the interval between the times of exposure and onset of symptoms. In the Minamata incident it has been calculated that severe intoxication was present at hair levels equivalent to 700 μg/gm (Skerfving et al 1970).

In the case of victims of the accidental U.S. poisoning (1969), serum levels rather than whole-blood levels were measured and these were about 3 ppm, as was the level in one specimen of cerebrospinal fluid from an affected child. Concentrations of mercury in the hair were determined and were as high as 2,000 ppm. Urine levels considered undependable, were reported as about 0.2 ppm in the three cases, but this level was also noted in the urine from the father of the affected children and he apparently was unaffected (Hinman 1970 and Likosky et al 1970).

Numerous values are available for Swedish individuals, none of whom showed symptoms resembling those of methylmercury poisoning. In many cases, blood values (Table 1) were correlated with the daily intake of fish containing known levels of mercurial residues.

A comparison of the available data on blood levels of individuals in Sweden who consumed high levels of fish containing mercurial residues with the estimated blood levels of intoxicated individuals in Japan shows that the highest level of mercury in blood reported in a few Swedish individuals exceeded the lowest levels among the toxic cases reported from Japan. The explanation is that there may be degrees of individual variation in sensitivity to methylmercury.

Table 1A. Content of Mercury (Hg) in Blood and Hair of Swedish Individuals

Persons	Approx. av. weekly intake of fish(g)	Residue of Hg in fish, ppm	Average levels of mercury in blood and hair, μg/gm							
			RBC		Plasma		Whole Blood		Hair	
			Average	SE	Average	SE	Average	SE	Average	SE
24	0	---	0.00185	0.00016	0.0013	0.0015	---	---	---	---
23	---	---	0.0069	---	0.0016	---	---	---	---	---
83	127	---*	0.01006	0.00029	0.00227	0.00012	---	---	---	---
10	150	---*	0.0083	---	0.0033	---	---	---	---	---
51	450	0.84(SE 0.05)	0.0062	0.0061	0.0018	---	---	---	7.9 (.81-31)† (46)†	±0.85
22	450	(highest)	0.032	0.0012	0.0093	0.00018	---	---	10.131	±1.563
29	450	(lowest)	0.044	0.0055	0.0057	0.0007	---	---	6.222	±0.809
1	220	0.6	0.029	---	0.0038	---	---	---	3.1	---
1	825	0.34	0.038	---	0.0047	---	---	---	---	---
7	(450-1,400)	---	(0.006-0.091)†	---	(0.003-0.018)†	---	(0.005-0.048)†	---	(1.0-11.2)†	---
17	(35-3030)	(1.1-5.8)†	(0.06-0.419)†	---	(0.001-0.069)†	---	(0.039-0.242)†	---	(3.9-33.8)†	---
18	"High"	(6.7)§	0.333 (0.033-1.2)†	---	(0.000-0.1)†	---	(0.007-0.65)†	---	(2.2-185)†	---
3	2,000	1-2	(0.047-0.522)†	---	(0.007-0.051)†	---	(0.024-0.268)†	---	(6.8-5.6)†//	---

*Salt Water fish.

†Maximal value

‡Range

§ Value available for fish eaten by only 1 of the 18 persons.

// Although Tejning reported this value as 5.6, it appears that a value of 56 would be more consistent with other reported values.

Source: Tejning 1970.

Measurements of blood levels of mercury and levels of intake via fish containing mercurial residues suggest that a direct relationship exists in man. For example, the data of Tejning (1970b) indicate that individuals ingesting approximately 0.019 and 0.034 mg/day of methylmercury had whole-blood levels of approximately 0.0164 and 0.0213 µg/gm and that an individual consuming approximately 0.8 mg/day of methylmercury had a blood level of 0.65 µg/gm, all without demonstrable clinical symptoms. A reasonable approximation appears to be that 1 mg/day of methylmercury (14 µg/kg/day for a 70-kg man) gives rise to an incremental whole-blood level of approximately 0.8 µg/gm at equilibrium. A concordant estimate associates an intake of 0.3 mg/day (approximately 4 µg/kg/day for a 70-kg man) with a total blood level of 0.2 µg/g (Skerfving et al 1969).

Swedish individuals who are considered to have reached the equilibrium state, between dietary intake and body burden of mercury, show a simple direct relationship between levels of mercury in blood and hair. The relationship is stated to be 60 µg of mercury/gm of hair, equivalent to 0.2 µg/gm of whole blood (or 0.4 µg/gm of red blood cells). (Skerfving et al 1969) Although hair concentrations are regularly much higher than blood concentrations, as indicated in the Swedish reports, in the case of Japanese individuals the ratio was quite variable, presumably because measurements were made at a time when body burdens were decreasing. Since hair levels integrate the exposure with time, they may have reflected the body burden when mercury intake was much higher.

Allowable Daily Intake.--As this report is being completed, the Swedish Commission on Evaluating the Toxicity of Mercury in Fish has released its report. In this, the commissioners set forth their recommendations relating to allowable intakes of methylmercury.

Essentially, they recommended the use of the "allowable daily intake" (ADI) concept under which warning is issued to consumers to restrict their intake of mercury-contaminated foods so as to keep their average daily intake within the recommended level.

The recommended ADI is based on the set of values outlined in an earlier paragraph as follows: The lowest whole-blood concentration for toxic symptoms was taken as 0.2 µg/gm; on the basis of a steady intake, they associated this with 60 µg/gm in hair and with a daily intake of 0.3 mg for a 70-kg man.

They then used a safety factor of 10 in defining the ADIs, giving the following "safe" levels: for whole blood 0.02 µg/gm, for hair 6 µg/gm, and for ADI 0.03 mg/70-kg or 0.4 µg/kg.

Even though only a safety factor of 10 was used, the restriction in terms of fish consumption is severe. Thus, with continuation of the warning to have no more than one meal of fish in the range of 0.2 to 1.0 ppm per week, the allowable weekly intake (7 x 0.03 mg = .21 mg/wk) would be supplied by 210 gm of fish containing 1 ppm of mercury. If fish containing 0.5 ppm of mercury were eaten daily, the limit (0.03 mg) would be reached by the daily consumption of 60 gm of fish.

Conclusions and Recommendations

The study group has concluded, on the basis of examination of the experience in Sweden and Finland, that the interim FDA guideline of 0.5 ppm of mercury in fish is, for the present, a sound basis for the protection of public health. However, the margin of safety may not be large, and uncertainties remain in regard to possible hazards where large amounts of contaminated fish are eaten. Resolution of these questions will require extensive further study.

Recommendations follow:

1. That comprehensive information on consumption of freshwater fish be gathered so that population subgroups likely to have had higher than usual dietary intakes of contaminated fish can be identified.

2. That the frequency-distribution patterns of fish ingestion be correlated with known levels of mercury and other neurotoxic chemical residues in fish in order to relate to possible neurologic responses in man. Similarly, persons or groups accidentally exposed to mercury from other sources should be identified for a similar study, including long-term follow-up.

3. That abortuses and stillborn infants in high-risk populations be studied for clues to the site and mode of action of toxic effects.

4. That experiments on animals be performed to determine maternal-fetal effects including possible genetic abnormalities, chromosomal aberrations, and teratogenic effects in relation to long- and short-term exposure at various levels. Also, the developing animal should be studied from the suckling stage to maturity to observe neurologic damage or behavorial dysfunction. Pathologic findings should be correlated carefully with exposures and tissue levels of methylmercury. The possible consequences of methylmercury transmission through the milk to sucklings, with and without transplacental exposure, should also be determined.

5. That the site and mode of cellular action of the methylmercury be elucidated with the objective of improving understanding of pathogenesis of disease and in the hope of developing better diagnostic, therapeutic and control techniques. It should be determined whether or not cumulative brain-cell damage can occur from a low-level chronic exposure to methylmercury and be expressed clinically or subclinically. In addition, more sensitive and informative diagnostic techniques should be developed to assess mercury intoxication before the expression of overt neurologic symptomatology.

6. That comprehensive physical and psychologic examinations and laboratory procedures be pursued with particular attention to the early detection of clinical and subclinical reactions. Refined motor and coordination tests and computerized electromyograms are among the possibilities. Such techniques which can be developed and those which exist should be applied in retrospective and prospective studies of exposed populations both here and abroad.

7. That, insofar as feasible, epidemiologic studies be coordinated, including those currently underway and those newly initiated.

8. That better guidelines of tissue changes and mercury levels in accessible tissues such as hair, blood, skin, and so on, be developed, since morphologic descriptions of determinations of mercury levels in brain and other internal organs currently are not available or feasible for early and nonfatal cases of methylmercury poisoning. Such studies of human beings and animals should be pursued when possible to correlate the mercury levels in accessible and inaccessible tissues.

9. That the role of fetal hemoglobin in the increased binding of methylmercury in fetal as compared to maternal red cells be clarified. Similarly, the relative extent and rate of accumulation of methylmercury in fetal as compared to adult brain should be established.

10. That experimental examination of possible synergisms of methylmercury with other neurotoxic chemicals (such as DDT, PCBs, and lead) be undertaken, since the latter are frequently found concurrently as residues in fish and other foods.

CHAPTER 2

MICROBIAL TRANSFORMATION OF MERCURY*

The methylation of mercury in sediments on river and lake bottoms is the process which, to a substantial degree, is responsible for current and potentially future contamination of aqueous systems and their associated biota. (See Fig. 1 [illegible]) By this methylation process also may play, through evaporation of dimethylmercury, a large role in atmospheric transport of mercury. Although there appears to be little evidence, it may well be that methylation also occurs in soils.

Despite the importance of the processes of methylation in converting mercury into the highly toxic monomethyl form and in mobilizing what otherwise might be [illegible] deposits of mercury in sediments into the highly transportable dimethyl form, we know little of the mechanisms involved.

To disclose the gaps in our understanding of the mechanisms, the major features of the process will be reviewed.

Natural methylation of mercury was suspected in the Minamata episode (Fujiki 1967 cited in Wood et al 1968), but the suspicion was put aside as being of no significance when methylmercury was identified in the discharge from the acetaldehyde plant (Irukayama et al 1962). Mercury has been shown to be methylated by aquarium and natural sediments (Jensen and Jernelov [illegible] and enzymatically by extracts of methanogenic bacteria (Wood et al [illegible]). The latter workers also found that small amounts of methylmercury were [illegible]ly. Both groups (Jensen and Jernelov 1969 and Wood et al [illegible]) found both monomethyl and dimethyl mercury as initial products; high mercurial concentration favoring the monomethyl form (Wood et al [illegible]) and alkaline pH favoring the dimethyl form (Larsson 1970). The latter [illegible] degrades to the monomethyl form at acid pH.

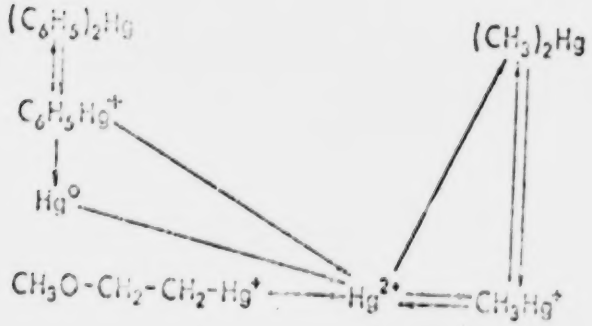
The tendency of [illegible] pH to favor a higher production of the more volatile dimethyl [illegible] would produce a larger discharge of methylated mercury [illegible] atmosphere; contrarily, a more acid pH should then favor [illegible] of the less volatile monomethyl form, (2) ready [illegible] greater proportion of dimethyl compound to the monomethyl [illegible] greater total retention, with less loss to the atmosphere [illegible] neutral or alkaline waters (Larsson 1970). [illegible] cited as possible factors (Johnels 1970) [illegible] remote acid lakes with high levels of mercury [illegible] known sources of mercurial contamination.

The reasoning here is that the natural (and large) volatilization of mercury to the atmosphere is reduced in acid waters. However, other possible

---

*Prepared by S. I. Shibko and N. Nelson

Figure 1. Conversion of inorganic mercury and some mercury-containing compounds to methylmercury.



From Jernelov, A.: Chemical Fallout, Chapter 4, p 72, 1969.

sources such as geologic deposits or selective atmospheric transport from remote industrial sites have not been eliminated.

All forms of mercury appear to be directly or indirectly capable of conversion to methylmercury. Paths are illustrated in Fig. 1 (Jernelov 1969). Indeed, it has been suggested (ibid) that phenyl mercuric acetate slimicides are more efficient sources of mercury for subsequent methylation than is inorganic mercury.

Although methylation of mercury will occur anerobically, it appears to be more efficient in aerobic systems. As noted in Chapter 3, production of oxygen deficiency has been considered as a theoretically possible but realistically impractical approach to the inhibition of methylation (Jernelov 1970). It appears that a variety of microorganisms can methylate mercury, and the major contributors have not yet been identified.

Microbiologic systems can also degrade organic mercury compounds. Their role in nature is unknown. Presumably, a balance is maintained in aquatic systems, which favors the synthesis of methylmercury. The following paragraphs summarize laboratory studies on degradation.

Tonomura et al(1968)and Tonomura and Kanzaki(1969) isolated a strain of Pseudomonas whose growth was inhibited only at concentrations of mercury 1,000 times that inhibiting growth of Escherichia coli and P. aeroginosa. Inhibition of growth was observed at a concentration of 450 ppm of mercuric chloride, 120 ppm of phenyl mercuric acetate, and 20 ppm of ethyl mercuric phosphate. Cells grown in the presence of phenyl mercuric acetate appeared to bind the material to the cell surface and then react in such a way as to cause vaporization of the mercury. The organism was capable of decomposing phenylmercuric acetate, ethylmercuric phosphate, and methyl mercuric chloride to form metallic mercury, and benzene, ethane, and methane which were identified by gas chromatography during decomposition of the respective mercurial compounds. Cleavage of the carbon-mercury bond in phenyl mercuric acetate and ethyl mercuric phosphate can be catalyzed by the cell-free extract in the presence of a sulfhydryl compound. This reaction is coupled with glucose dehydrogenase which catalyzes the formation of NADH and NASPH (Tonomura and Kansaki 1969).

In addition to the possible role of microbial systems in the circulation of mercury in the biosphere, similar microbial systems in the gut flora of birds and mammals may be involved in the metabolism of mercury compounds. For example, hens convert a small proportion of ingested mercury compounds (phenyl mercuric hydroxide, methoxy ethyl mercuric hydroxide, or mercuric nitrite) to methylmercury, which appears in the organs of the hen and eggs (Kurmae et al 1969). At present it has not been definitely established that the methylation process can occur in mammals. However, microbial systems in mammals appear to be involved in the metabolism of methylmercury. Norseth (1969) has shown that in the rat biotransformation of protein-bound methylmercury in the cecum is the major source of

fecal inorganic mercury. Since this reaction was limited to the lower part of the small intestine or cecum, Norseth postulated the involvement of microorganisms.

Recommendations

Since a possibly important means of preventing continuing production of methylmercury in aqueous systems from present deposits will depend on finding means to interrupt the biologic methylation process, it is urgent that the controlling factors be understood. Thus, it is recommended that:

1. The factors controlling the methylation and degradation of mercury compounds, particularly in the bottom sediments of waterways, be intensively examined.

2. The role of microbial systems in the gut flora of animals in the metabolism of mercury compounds be established.

CHAPTER 3

SOURCES, DISTRIBUTION, AND CONTROL*

Mercury is distributed throughout the environment. In Sweden the man-caused contamination by mercury is confined to the southern half of the country. Major sources or residuals exist near mercury-cell-type chlor-alkali plants which may or may not be operating at the present time. Similarly, heavy residual contamination persists in many bodies of water from earlier mercuric slimicidal discharges from pulp-manufacturing plants. Thus, vast amounts of previously discharged mercury still exist. Fish contaminated above background levels, in some cases above acceptable limits, are found in some remote waters where there are no known or apparant sources of mercury.

Decontamination through natural processes is extremely slow and, considering the large volumes of mercury contained in some bottom sediments, it is quite conceivable that some waters will remain contaminated for 100 years or more. The levels of mercury in fish indicate that in a very few cases the level is decreasing with time, but this is the exception rather than the rule. From the standpoint of persistence, rivers may clean themselves more quickly than lakes which have both lower rates of water turnover and less current. This viewpoint is supported by some data from both caged and captured fish. For a fuller discussion of this, see Chapter 4.

Sources and Control

Sources of mercury in Sweden and in other industrial and agricultural countries fall into the following categories: (1) chlor-alkali plants, (2) industrial processes involving the use of mercurial catalysts, (3) slimicides, used primarily in the paper-pulp industry, (4) seed treatment, (5) burning of fossil fuels, (6) natural occurrence from geological formations, and (7) miscellaneous sources, considered in the following discussion. (See Appendix B for projected trends in the use of mercury.)

Discharge From Chlor-Alkali Plants.--In Sweden in 1967, mercury from this source ranged from 51 to 85 gm/ton of chlorine produced. Previously, discharges were as much as 10 times these values. Present and anticipated discharges in Sweden are summarized in Table 2.

The methods that contributed to this reduction in the discharge of mercury include the following procedures which are being applied or are planned:

1. Cooling the hydrogen gas to less than 0° C at 2 atmospheres of pressure and returning the condensate to the decomposer.

---

*Prepared by Lowell A. Van Den Berg

Table 2. Mercurial Discharge from Chlor-Alkali Plants in Sweden

	Loss of mercury, gm/ton of chlorine		
Loss to	Range Aug.1967	New plant at Stenungsund, 1969	Technically possible in 1970
Water	30 to 40	0.55	0.01 to 0.1
H_2 gas	5 to 10	0.4	0.01
Alkali	1 to 10	0.8	0.01 to 0.5
Ventilation	15 to 25	1.0	0.5
Total	51 to 85	2.75	0.53 to 1.11

2. Returning the condensate, obtained by cooling the chlorine gas, to the brine solution.

3. Separating the waste streams and using epoxy on concrete floors to prevent the entrapment of mercury.

4. Enlarging and improving sedimentation basins.

5. Filtering wastewater through activated charcoal.

6. Treating wastewater with disulfide and subsequent coagulation, sedimentation, and filtration.

7. Treating wastes by means of ion exchange, probably after pretreatment by another method.

8. Improving procedures for reactivating cell anodes.

9. Recirculating all water used in production.

Mercurial Catalysts.--Only one plant in Sweden used mercury as a catalyst to convert acetylene to acetaldehyde. Losses of mercury from that plant were estimated to be 300 kg/year. The process at this plant has been changed to the conversion of ethylene to acetaldehyde, which does not require the use of mercury.

Slimicides in the Pulp and Paper Industries.--The pulp and paper industry formerly used mercurial compounds to control fungi in wood pulp and to control slime in pipes and machinery. This practice has been banned but large deposits of mercury still exist in sediments downstream from these plants. These deposits act as a continuous reservoir to release mercury to the overlying waters and aquatic life.

Additional contamination from this source of mercury virtually has been eliminated in Sweden and Finland by banning the use of mercury slimicides by the pulp and paper industry.

Seed Treatment.--The use of mercurial seed dressings has been reduced significantly, and a reduction in contamination of the environment has resulted.

Control is under way in Sweden with the replacement of alkyl-mercurial pesticides with the less-toxic alkoxy-alkyl mercurial compounds and the restriction of the use of the latter during the spring planting, except when justified by demonstrated need. In addition, search for nonmercurial seed-treating agents is under way. (See Chapter 5 for details.)

Burning of Fossil Fuels.--Fossil fuels have not been evaluated as a source of mercury for Sweden. Based on information presently available, coals in the United States contain mercury in concentrations from a few parts per billion to several parts per million.

It is reasonable to estimate that the average concentration is, at least, one part per million. The annual consumption of 500 million tons of coal per year would contribute one million pounds of mercury per year to the environment (about 450 metric tons). This value does not include that mercury contributed from the refinement and use of products from crude oil which may contain even higher concentrations of mercury.

Natural Occurrence From Geological Formations.--Some geological formations contain mercury that is released to the environment through the process of leaching and volatilization. Although this source of mercury is uncontrollable, it must be considered when evaluating concentrations in air and water used by man. This may account for high concentrations of mercury found in some isolated bodies of water which have no known man-made sources of contamination.

Miscellaneous Sources.--There is a large variety of miscellaneous sources that present possible mercurial contamination to the environment. In Sweden, as elsewhere, their contribution is for all practical purposes not known. A partial list follows:

1. Refuse from hospitals, laboratories, and dental clinics.

2. Disposal of thermometers, barometers, aerometers, relays, rectifiers, switches, fluorescent tubes, mercury lamps, and batteries.

3. Processing or use of raw materials containing mercury--such as carbon, coal, chalk, phosphate, pyrite, and so on.

4. Manufacture of and residue from paints and impregnating agents which contain mercury to impart mildew-resistance.

5. Refining or redistillation of mercury.

6. Use of mercurial compounds to prevent mildew in commercial laundries.

7. Use of alkali produced in chlor-alkali plants, which may contain as much as 4 to 5 ppm of mercury. (Swedish regulations require that the level of mercury in alkali be 0.5 ppm or less.)

For the most part these sources have not been quantified or even systematically identified. Clearly, an inventory of such sources must be undertaken and assessment made of their contribution to environmental contamination before control can be effective.

Decontamination

Experiments conducted on the transformation of various mercurial compounds have revealed useful information to consider for the decontamination of mercury-polluted waters.

The oxygen content of the water-sediment system is one of the most important factors (Werner 1967, Jernalov 1968b). If there is an oxygen deficit in the bottom waters, hydrogen sulfide can be formed and the inorganic mercuric ions will precipitate as highly insoluble mercury sulfide. In completely anaerobic systems the rate of methylation of mercury is reduced (Miettinen 1970). In the presence of hydrogen sulfide, the redox potential of +80 mV, which is necessary for oxidation of elemental mercury to mercuric ions, is not reached (Jernalov 1968a).

It has been demonstrated that the methylation of mercury can yield at least two different final products--monomethyl mercury or dimethyl mercury (Jensen and Jernelov 1969). These two products behave quite

differently. The monomethylated product is directly accumulated by organisms in the water, while the dimethylated form is purported to leave the limnic ecosystem and go into the atmosphere. The most important factor to influence the net outcome of the methylation process is the pH of the water and sediment. High pH values give higher yields of dimethyl mercury (Olsson 1968). (See Chapters 2 and 6 for additional discussion.)

Metallurgists have shown that freshly ground quartz and silicate minerals have surface layers with disrupted lattices that are very efficient in adsorbing heavy metal ions (Lidstrom 1968). Further investigations revealed that fish from lakes receiving wastes from ore-dressing plants, and therefore large quantities of ground silicate, are usually low in mercurial content (Freyschuss and Jernelov 1968).

Experiments conducted at the Swedish Water and Air Research Laboratory were designed to evaluate the effectiveness of (1) increasing the pH of the hypolimnic water and bottom sediment, (2) covering the mercury-containing sediments with inorganic material, and (3) introducing inorganic materials with very strong adsorptive capacities (Landner 1970).

To evaluate method 1, an aquarium was prepared with a 5-cm layer of fibrous sediment containing 600 ng of methylmercury/gm (dry weight) and covered with an 0.5 to 1.0-cm layer of lime followed by a 5-cm layer of sand. Fish (Eucloperca lucioperca) in an aquarium with the same fiber not treated with lime and sand accumulated about five times more methylmercury than did those in the treated aquarium.

Experiments with mercury-contaminated sediments covered by layers of varying thicknesses (0 to 20 cm), of inorganic sediments, method 2, with and without macrofauna, Tubificidae (oligochaete worms) and Anodonta (a bivalve), revealed that (1) in the absence of Tubificidae, methylmercury accumulated in fish only when the sediment was uncovered, (2) in the presence of large populations of these worms, fish accumulated methylmercury when the covering layer was less than 2 cm, (3) in the presence of Anodonta, which stirs the sediment, leakage of methylmercury occurred if the covering layer was less than 9 cm. The population densities of macrofauna used in these experiments were much higher than occur in nature. Therefore, the thinner layers of covering materials might be efficient under natural conditions.

Tests designed to evaluate the effectiveness of ground silicate, method 3, on the uptake of mercury by fish from sediments contaminated with metallic mercury, ionic mercury, ions, and phenyl mercury revealed that there was no reduction in uptake when the pollutant was phenyl mercury. A decrease in uptake by a factor of two occurred when inorganic mercury was the pollutant. The silicates used were not freshly ground and the material did not completely cover the sediments. Therefore, under more ideal conditions, better results probably would have resulted.

Principles discussed by Landner (1970) to control the transformation of mercury in water include the following:

1. Introduce oxygen-consuming materials to create continuous anaerobic conditions in the sediments, thereby reducing methylation.

2. Increase the pH of the sediments to favor dimethylation and increased volatilization. (See Chapters 2 and 6.)

3. Cover the sediments with fresh finely divided materials, with high adsorptive affinity--for example, quartz and silicates.

4. Cover the sediments with inorganic inert materials of any type--that is, bury them.

5. Remove mercury-bearing sediments by dredging or pumping.

The first two are impractical, and plans to evaluate the other three are being formulated in Sweden.

Experimental studies planned or started include (1) an untreated control area, (2) a dredged area, (3) an area to be covered with ground silicate, and (4) an area to be covered with inert sediments dislodged from upstream river banks.

An allocation of the order of $150,000 has been made for the planning of these studies, but the actual engineering execution will require considerably larger sums. The work will be undertaken beginning next summer and should be closely observed by representatives of the United States.

Recommendations

1. Initiate immediately an intensive program directed toward the decontamination of existing contaminated waterways.

2. Seek improved methods for the removal of mercury from wastewater discharges.

3. Develop methods for the treatment and disposal of residues and sludges that result from treatment processes which will prevent contamination of the environment with mercury.

4. Evaluate the use of biologic organisms--that is, caged fish, shellfish, snails and so on--as monitors of old and new sources of pollution and of treated wastewaters containing mercury. The accumulation of mercury in the body tissues would be the basis for evaluation.

5. Evaluate the contribution of mercury discharges to the atmosphere, such as those which may be produced by aeration of mercury containing wastes, incineration of solid wastes or sludges, or combustion of digestor gases in waste treatment plants.

6. Evaluate the environmental contribution from the disposal of mercury in land fills and dumps through measurements of the movement of mercury and its compounds into soil, surface and ground water, and air.

7. Evaluate processes of treating public water supplies to determine the efficiency of removal of the various forms of mercury.

8. Determine whether there is a minimal level of permissible mercury discharge that will not result in cumulative concentrations in bottom sediments and the aquatic food chain, with special emphasis on nonflowing and slow-moving bodies of water.

9. Monitor all uses of mercury in federal installations and areas of federal responsibility. The federal government should develop effective methods and guidelines for the disposal of equipment and wastes containing mercury.

10. Require industries using mercury-water contact processes to monitor all effluents for mercury content.

11. Recommend that precautionary measures be taken by all users and possessors of mercury or mercury compounds for any purpose to prevent accidental spills or losses to the water environment.

12. Encourage completion of present efforts to establish a complete inventory of mercury uses, users, and discharges as soon as possible.

13. Evaluate the contribution of natural (geological) and incidental (e.g., coal combustion) sources of mercury to the biosphere.

CHAPTER 4

ECOLOGIC EFFECTS OF METHYLMERCURY CONTAMINATION*

Wildlife served its traditional role as an early warning system for man when problems with mercury arose in Sweden. The first alarm sounded in the middle 1950's when populations of the yellow bunting dropped catastrophically. Deaths, reproductive failures, and population declines of both seed-eating and raptorial birds were soon noted (Otterlind et al., 1964). Toxicity from mercury, used in seed dressing to prevent cereal diseases, was suspected. Experimental, chemical, and pathologic work demonstrated that the suspicions were correct. News of the Minamata problem in Japan led to broader and deeper studies.

Analyses soon revealed that mercury pollution was serious in Swedish lakes and rivers and that seed dressings were not the sources of this contamination. Waste and leakage from pulp mills and chlor-alkali factories were chiefly responsible. The result was local and spotty contamination, often heavy. Many lakes and streams remained free or nearly free of mercury. Even today, most waters of Sweden are not and need not be monitored; in fact, only 1% of Swedish waters are blacklisted because of the levels of mercury in fish. This localization of contamination means that one must look at the right spots to find it. Early efforts to repeat Swedish findings in the United States failed because the animal samples that were taken did not come from near sources of mercury despite the fact that they were taken from some of the most polluted estuaries of the eastern United States.

As other sections of this report explain, Swedish investigators found that most of the mercury in animal tissue was methylmercury and that other forms of mercury were able to pass into the methyl form in nature, owing to microbial action in bottom sediments. The process is not well understood and requires far more study to determine the conditions that permit methylation and demethylation and the rates at which these processes occur in nature. It seems evident, however, that methylation is a common and powerful natural force, for methylmercury predominates in animals even where other forms of mercury have been released. Methylmercury often comprises 99% of the mercury in animal tissue.

This is important, for of all forms of mercury, methylmercury is the best absorbed and the most slowly lost. It accumulates in the brain, where it destroys cells and causes neurotoxicity and death of men and animals. It passes through the placenta and damages the young just as it passes through the oviduct into eggs, where it reduces hatchability. It accumulates so well that repeated minute intakes during a prolonged period can kill or create permanent disability. These points are documented for man in this report, but they apply to animals in nature with even greater force. This is because animals living in contaminated areas are steadily exposed to heavily polluted food, as man rarely is, and because some of them excrete mercury far more slowly than man does. In addition, animals that live in water can pick up much mercury directly from the water, probably in some instances far more than they get from their food.

---

* Prepared by W. H. Stickel

The traditional food-chain build-up may not occur with mercury. Hannerz (1968) found that uptake by animals was not related to trophic levels, but to such factors as metabolic rate and food habits. It is true that predators usually contain more mercury than their prey, but levels can be high near the base of the food pyramid. For example, Johnels, et. al., in 1968 reported that residues of 1.4 to 17 ppm were found in aquatic insects that normally had about 0.05 ppm. Pike from the same area (below a pulp mill) had 3.4 to 8.0 ppm in muscle. Records of more than 2.5 ppm in pike muscle are rare in Sweden. As the residues in invertebrates were so high relative to those in pike, this example seems to support Hannerz' view that no true food-chain accumulation occurs. It is true, however, that levels of mercury in animals are thousands of times greater than those in the surrounding water.

Mercury in Fish

Most Swedish fish have about one third to one half as much mercury as do pike in the same waters. Health authorities in Sweden sometimes allow fish other than pike to be eaten from waters that are blacklisted.

Blacklisting of waters in Sweden is done when a sample of five pike shows residues of 1 ppm or more of mercury in most of the five. If one or two of the five have a higher level, another sample may be requested. Statisticians have advised a sample of at least 11, but costs rule this out. At present, the judgment is made more or less subjectively from the sample of five. If residues are between 0.2 and 1 ppm, Swedes are advised to eat fish from these waters no more often than once a week. The Swedish actionable level of 1 ppm is considered too high, but if 0.5 ppm were the criterion, as in the United States and Canada, five times as many waters would be blacklisted and monitoring costs would be out of hand. We estimate that the present monitoring costs in Sweden may be between 200,000 and 500,000 U.S. dollars annually.

When comparing residues of mercury for blacklisting purposes, levels in pike are adjusted to fit a pike weighing 1 kg, or about 2.2 pounds. This is done because pike keep growing and keep increasing in concentration of mercury. The curve of the increase in the level of mercury tends to flatten in large old pike, but it does not seem to reach a steady state.

Sweden chose the pike for monitoring because it is nonmigratory, is long-lived, has high residues, has few if any stunted populations, has wide distribution, and normally grows throughout life. These criteria seem worthy of consideration in selecting species where pike are not available.

It is worthy of note that levels of mercury in pike may be less than expected in biologically rich alkaline waters. Apparently the biologically available mercury is divided between enough organisms to hold down the amount in pike. There is another reason, however, that the total mercury in such sites could be misleading: eutrophic waters

often have bottoms rich in H_2S, and this may react with mercury to form HgS, which is insoluble and hence of low biologic availability.

We are uncertain about how high residue levels in fish may run and about the effects of high levels on fish. Fish and shellfish found dead at Minamata are said to have contained 9 to 24 ppm of mercury on the usual wet-weight basis (Lofroth, 1969); presumably some or all of these levels were lethal. Living wild pike have high levels in comparison with those of other fish. One Swedish pike, perhaps a very large one, had more than 17 ppm (wet weight?) in muscle (Larsson, 1970). The highest levels we have seen mentioned for the standard Swedish pike of 1 kg are 9.8 and 8 ppm, and even these levels have been found rarely. On the other hand, it has been shown that muscle levels in pike experimentally killed by methylmercury varied from 5 to 9.1 ppm and averaged 6.4 and 7.4 in two groups (Miettinen et al, 1970). Clearly there is an overlap between the curves of residue distribution in living wild pike and experimentally killed pike. One is tempted to hypothesize that few pike can exist in the wild with as much as 6 or 8 ppm of mercury in muscle. Is it not possible that Swedish pike have died from mercury-poisoning in the wild and that the losses were gradual and unobserved?

Possibly higher levels at death could be created in pike by lower dosage for longer intervals than Miettinen and co-workers employed. However, the whole-body levels of 11.1 and 23.2 ppm that they reported for the two groups of pike are impressive in comparison with the Minamata figures of 9 to 24 ppm. Fish from Niigata had up to 15 ppm, mostly far less, when sampled after the tragedy there.

Some of the fish at Minamata were reported to be floating at the surface, or splashing the surface while swimming on their sides, or swimming vertically. The levels of mercury in these affected fish do not appear to be known, but the observations reinforce the point that death of fish from mercury poisoning can and has occurred.

A few other data suggest that Swedish pike may have been affected. Hannerz told us that when pike were reared in water containing 0.1 ppb of methylmercury for a season and were then placed in clean water, they underwent continuing mortality. Scattered mortality of this sort could not be detected in nature, for the affected fish probably would be eaten by predators as soon as they began to become uncoordinated and to have sensory dysfunction.

Hannerz experimented with fish having levels of mercury like those in nature. The fish seemed normal, but they died suddenly when moved from one tank to another (Johnels, et al, 1969).

Another piece of evidence, mentioned orally by Johnels, is that pike of a population from below a pollution source definitely weighed less at each age than those taken upstream from the source. This is especially significant, because no other population of stunted pike is known to Johnels.

Behavioral effects on Minamata fish have been mentioned. Presumably these represented late, and perhaps terminal conditions. An unpublished experimental study by R. E. Lindahl, Uppsala University, for which we have seen the data, has shown behavioral inadequacy of fish exposed to methylmercury. The effects increased with treatment level and with length of exposure. The exposure was relatively severe, however, and we do not know what residue levels the fish attained.

We received no report of reproductive effects of mercury on fish. Experimental work on this subject appears to have been neglected. Indeed, the whole field of effects of methylmercury on fish seems to have received little study. Both reproductive and behavioral tests could be made readily under controlled conditions. It would be more difficult to determine what minimal levels in food and water were dangerous to fish during long periods and what residue levels these long low exposures created. Perhaps such work could be done by extrapolation from shorter tests of effects and retention at several exposure levels. These should reveal, for various species, what effects and what residues would result from known exposure that simulated those in nature. In general, long tests are needed, because symptoms in animals, not just fish, may be delayed for weeks or months.

An admirable start on this work has been made by Miettinen and his colleagues in Finland (Miettinen et al, 1969) and by Backstrom in Sweden (1969). Using radiochemical and autoradiographic techniques, they have shown how methylmercury is distributed through the organs of fish and how this distribution changes with time. But most important from the ecologic standpoint, they have shown for species after species of fish that methylmercury is lost at an extremely low rate. Backstrom (1969) found a little loss from most tissues after 30 days, but levels in brain and muscle were still rising.

Miettinen and his associates have shown in a series of papers, still largely unpublished, that the loss of methylmercury from fishes has two components, fast and slow. The fast loss occurs early, while mercury is being redistributed through the body, and lasts only a few weeks. The subsequent loss from established binding sites follows slowly; indeed, the half-life estimated from this component is hundreds of days--on the order of 2 years. These rates mean that fishes--and perhaps other lower vertebrates--reduce their content of methylmercury many times more slowly than do the higher terrestrial vertebrates. The same workers also have shown extremely low rates of loss from aquatic mollusks and crayfish, but they have noted distinct species differences.

This slow loss is one vital reason for fish being the major source of mercury for man. The other, of course, is that fish are continually resupplied with mercury from the water as microbial methylation provides more methylmercury from all other forms of mercury in the bottom sediments.

The slow rates of excretion by fishes and the continuing supply of mercury from sediments give little hope for quick improvement in fish residues. Swedish experience confirms this, in the main, for pike residues in most lakes have dropped little if at all since mercury bans became effective in early 1966. These lakes tend to be biologically poor, acid lakes. A few lakes, about three, apparently have had mercury levels in pike drop to a demonstrable extent. Sample sizes militate against more specific statements.

Rivers have a better chance, owing to flushing. Hasselrot's work in exposing salmon in live-boxes above and below former sources of mercury has shown much improvement within 3 years, at least in some rivers (oral communication). In the river above Göteborg, for example, levels in salmon livers dropped from about six to nine times the background level to about one to three times that level. In at least two other polluted rivers, livers of test fish now give about the same readings above and below the former sources. Certain bottom sediments also have lost part of their mercury content, especially below pulp mills, where phenyl mercuric acetate on pulp fibers may lend itself well to either washing away or to conversion to monomethyl or dimethyl mercury. Some drop in sediment levels of mercury can be noted in rivers even below chlor-alkali plants. Although this may represent mainly transport downstream, such dilution can be helpful in reducing areas of dangerous levels.

Mercury in Birds

Birds have been seriously--sometimes catastrophically--affected by mercury. The best known and most dramatic source in Sweden was treated seed. Aquatic contamination had less sudden and dramatic effects, but its world-wide ramifications are just beginning to be known.

Acute toxicity of methyl mercury to birds results from levels about the same as those toxic for laboratory mammals, around 12 to 20 mg/kg, to judge from tests with relatively few species. Chronic tests with birds have been made largely with seed operationally dressed with about 15 to 20 ppm of methylmercury (Borg et al, 1969; Tejning, 1967). Such seed killed pheasants in 29 to 61 days and jackdaws in 26 to 38 days.

Mercury residues in liver-kidney composites of birds experimentally killed by treated seed ranged from 30 to 130 ppm for pheasants, 70 to 115 ppm for jackdaws, and 50 to 200 ppm for magpies. Muscle levels in pheasants ranged from 20 to 45 ppm. One must conclude that liver-kidney residues of 30 ppm or more in birds indicate critical exposure and perhaps death; normal levels, by contrast, are less than 1 ppm. We may think of all levels greater than 1 ppm as representing some degree of contamination.

Using these criteria in judging wild birds, both those found dead and those taken alive, Borg et al (1969) concluded that more than half of the bird populations of Sweden were carrying increased levels of mercury and that many birds were killed outright. Population declines occurred in a number of species.

Tejning (1967) demonstrated that pheasants could readily eat enough dressed seed to create the observed tissue levels of mercury and to cause death. Seed is often available on the surface, especially at the turn-around areas at the ends of fields.

These effects were complicated by the presence of aldrin and dieldrin in seed dressing, and the amount of aldrin or dieldrin in birds was not determined. The data on residues of mercury, however, make it possible to say that mercury had lethal effects in itself, regardless of the contribution of other compounds. The use of aldrin and dieldrin is no longer legal in Sweden.

While seed-eating birds were declining, predatory birds that fed on them--or on fish--were in a worse situation. This secondary poisoning was proved: meat from hens killed with methylmercury killed goshawks and ferrets within two to three weeks. All studies we have seen support the view that free and protein-bound methylmercury acts in the same way and with equal force.

Hawks and owls were hard-hit. Wild seed-eaters had liver residues ranging up to 140 ppm, but predatory birds had levels up to 300 ppm. As predatory birds are rarely numerous and have relatively low reproduce rates, they might have become exterminated over large areas if the release of mercury had not been stopped. Just how low their numbers did drop, we may never know. However, since the ban on seed dressing with methylmercury took force in 1966, goshawks have been retovering and their residues of mercury have dropped (Larsson, 1970).

The seed-eaters seem to have responded more promptly. Levels of mercury in pheasants were back to normal the year after the ban. Pheasants are largely an annual crop: thus, the normal levels probably represent the lack of contamination of new birds, not almost total losses from old birds. Levels in wood pigeons definitely dropped between 1964 and 1966. Wood pigeons and rooks have recovered well. These data indicate that the mercury agents now used in seed dressings in Sweden are safe for birds, as currently used. The methoxyethyl-mercury seed dressings now used are employed only when and where needed. Beyond this, they are less toxic and are much more easily excreted than are the methylmercury dressings.

Mercury is deposited in feathers and other keratinous tissues in large amounts, far more than in other tissues. This has made it possible for Swedish workers to trace the historic increase of mercury pollution by analyzing feathers from museum skins. The results (Berg et al, 1966; Joanels et al, 1969) show that residues in seed-eaters, specifically in pheasants and partridges, rose sharply after 1940, corresponding to the adoption of methylmercury treatment of seeds. At the same time, levels in goshawks, peregrines, and eagle-owls rose even more sharply, to 10 to 20 times their earlier levels. These birds feed upon the seed-eaters and obviously obtained their sudden and heavy contamination from them. On the other hand, residues in two fish-eaters, osprey and great crested grebe, rose slowly after about 1890, corresponding to the gradually increasing contamination of waters from industrial sources. Today these two species have about three times as much mercury in contaminated areas as in non-contaminated areas (Larsson, 1970).

The tendency for mercury to be deposited in growing feathers, claws, and beaks is so strong that feathers and other keratinous structures will eventually contain nearly all of the mercury in a bird (Tejning, 1967; Backstrom, 1969). As birds molt once or twice a year, they must shed large proportions of their mercury in this way.

The half-life of mercury in birds does not appear to be excessive by comparison with that in mammals. Ulfvarson (1962) considered the half-life in chickens to be 35 days. Bäckström (1969) found little loss from male quail (Coturnix) in 30 days, especially from brain and muscle.

Females, however, had a marked loss in this period, largely because of excretion in eggs. Borg et al (1969) found a relatively rapid loss from pheasants. In 2 months, one third to one half of the mercury was gone from the liver and kidney; a similar loss was suggested by the few muscle analyses that were made. In 6 months, liver and kidney levels in experimental pheasants dropped greatly: from 13, 26, and 30 ppm at the time exposure ceased to an average of about 0.25 ppm. If we take this as a drop from 25 to 0.25, the loss from liver and kidney was 99% in 6 months.

Wild pheasants showed rapid seasonal changes; liver levels rose sharply from April to May, when treated seed became available, then dropped sharply from July to September. This supports the Alberta, Canada, experience in which residues averaging 0.45 ppm appeared in pheasant muscle in early summer, but had declined to an average of less than 0.1 ppm by late September (Wishart, 1970).

Data for chickens and pheasants may be poorly applicable to predatory and fish-eating birds. For the latter, there seems to be a single report, based on replaced feathers, indicating that the half-life of methylmercury in the osprey is of the order of two to three months (Johnels et al, 1968). This suggests that the osprey may lose its mercury at about the same rate as does man, and man loses it considerably more slowly than do laboratory rodents (discussed later).

The half-life data given here are based largely on the liver and kidney, which are organs of clearance rather than organs of storage. We think that data on the half-life of mercury in the whole-body or in muscle should be obtained, not only for seed-eating types of wild birds, which are often ecologically resilient, but also for fish-eating and flesh-eating birds, for numerous species of these birds are declining rapidly in many parts of the world. It is entirely possible that the predatory species are physiologically less able to handle foreign chemicals than are seed-eaters; this appears to be true for chlorinated hydrocarbon pesticides in both birds and mammals.

As predatory birds are usually too scarce to be sacrificed in numbers for analysis, careful consideration should be given to studying half-lives of mercury in wild birds through the use of feathers--a tissue that may be superior to blood or muscle for studying changes in individual birds or groups of birds. Feathers should be even better for monitoring contamination in the field. For once-a-year monitoring however, the avian egg is unexcelled because of ease of collection and because its level of mercury can be related to reproductive effects. However, knowledge of the relationship of egg residues to reproductive success will have to be refined by further experimentation and field study.

The reproduction of birds has been severely reduced by dietary exposure to mercury in both field and laboratory. Tejning (1967) found heavy reduction in reproduction and hatchability of hens' eggs when only half of the diet was comprised of dressed seed. His birds tended to lay eggs about the pen instead of in the nest. Borg et al (1969) found that when dressed seed was fed to pheasants for as long as 9 days, hatchability

dropped briefly to zero and thereafter was about one third below the previous rate. In this short feeding, the authors found no drop in egg production and no abnormality of chicks. The pheasant egg residues associated with poor hatching in experiments were 1.3 to 2 ppm, but the data are not extensive. In the field, unhatched pheasant and partridge eggs had about 3 ppm. White-tailed eagle eggs that failed to hatch had 3.5 to 11 ppm, but these figures may prove to be high if no allowance was made for loss of moisture from addled eggs. Eagle eggs are seldom collected until far gone, and it is necessary to correct for the original weight of the egg; this correction is easily made from the volume or other measurements.

The residues in eagle eggs were associated with a drastic impairment of eagle reproduction in Sweden. Numerous other species also underwent reproductive failure at the same time they were undergoing increased mortality (Borg et al, 1969). Populations decline rapidly under these conditions and slow breeders can recover but slowly--and only if other factors are favorable.

Finnish workers reported on five white-tailed eagles killed by mercury. They also stated that their few remaining pairs of eagles usually fail in reproduction (Henriksson et al, 1966).

One of the most useful things that could be done in this field of work would be to establish experimentally the levels of mercury in eggs that indicate the lower levels of damage in various groups of birds, especially the fish- and flesh-eaters. This will have to be done, and then related to field levels, before we know what is happening to many avian populations around the world. Mercury certainly does not account for all problems, but there is a chance that it contributed to certain avian population declines, reproductive failures, and instances of abnormal behavior that have been attributed to other factors.

Mercury in Mammals

Mammals are not resistant to mercury poisoning. Cats died at Minamata before people did. Cats have been killed experimentally by feeding them fish and shellfish from Minamata or Swedish fish naturally contaminated at 5.7 ppm. Borg et al (1969) listed a Swedish marten, polecats, and a fox whose residues, behavior, and autopsy findings indicated death from methylmercury. These are all predators. Herbivores had low residues of mercury, usually well below 1 ppm, as did herbivorous birds that were not seed eaters.

Other parts of this report detail the serious effects of mercury passing the placenta and entering the fetus. Presumably this affects wild mammals as it does man. It is to be hoped that study of this problem from the viewpoint of human medicine will include enough groups of mammals to yield some concept of the levels that are dangerous to various mammals in terms of both intake levels and the associated tissue levels.

In this connection, however, it may be pointed out that natural selection in the wild rapidly weeds out defective individuals. Only effects gross enough to have population results are of such ecologic consequence. For this reason, studies of the intensity employed in human medical research are not required for ecologic purposes. Instead, the needs of ecology and conservation are met best by measuring effects on mortality and reproduction, which govern populations, and determining the residue levels that are diagnostically associated with these effects.

Persistence in the body is one factor of much importance in determining population effects. Mammals vary widely in the persistence of methylmercury. The half-life may be as little as 3.7 days in mice, is 15 to 70 days in rats, was 20 days in a young dog, and is best estimated as 70 to 74 days in man, according to Swedish and Finnish data. The rate of loss for man is estimated at about 1%/day.

The most extreme example of slow loss among mammals pertains to the endangered, landlocked subspecies of seal, Pusa hispida saimensis, from lake Saimaa in Finland. Perhaps 250 individuals of this race remain. One found sick and ataxic proved to have 197 ppm of mercury in muscle and 210 ppm in liver, ample to account for its condition. Yet levels in the local fish were low. Tests revealed that a seal of this species had a rate of loss of mercury slower than that known for any other mammal and about like that of fish (Tillander et al. 1970). With this slow loss, even a low level of mercury in food could cause serious accumulation. There is no reason to think that Pusa hispida is unique. Other fatty, highly aquatic mammals may prove to have similar rates of loss and thus may resemble fishes in this regard.

Conclusion

The problem of mercury to date has focused on man and on birds that ate dressed seed. There can be little doubt, however, that the greatest population damage must be sought among species that are obligate eaters of aquatic animals, are relatively scarce to begin with, and have a low reproductive rate. Eagles and ospreys, mink and otters, are obvious candidates. Kingfishers are reportedly scarce in certain lands. The list could be extended to include hundreds of species. Most of these cannot be studied in depth, but enough should be sampled from suspect areas to clear the picture, and a few selected species of different groups should be studied experimentally to permit interpretation of residue data for the rest.

Effects on aquatic invertebrates and fishes are poorly known. We suspect that further research will show increased mortality, as well as behavioral and reproductive effects, in many groups of aquatic animals subjected to high environmental levels of mercury. Comparative studies of species composition in mercury-polluted areas may provide good leads by revealing which groups are scarce or absent where mercury contamination is high. We have not seen such studies.

Maximal attention should be paid to rare species, many of which are endemic to small areas. Such forms may have little ecologic flexibility or resiliency; they can be lost easily once a decline sets in.

Recommendations for Research

1. Compare the occurrence and abundance of invertebrate and vertebrate species in aquatic areas that are and are not polluted with mercury to learn which species and groups are most severely affected.

2. Determine, for different regions of the country, which aquatic organisms (plants, invertebrates, or vertebrates) are most prone to accumulate large residues of mercury. This would point out indicator organisms, would reveal which organisms are the most dangerous sources of mercury if eaten by man or other animals, and would draw attention to organisms that may be in trouble because of their own high content of mercury.

3. Study the fish-eating birds and other widely ranging animals that depend on food from the aquatic environment to learn how their populations are holding up in mercury-contaminated areas as compared to non-contaminated areas. The burdens of mercury carried by these animals should be determined.

4. Study the reproductive success of the animals just mentioned, in mercury-contaminated areas. Relate the degree of reproductive success to the amount of mercury in eggs and other tissues, insofar as this can be done from field studies.

5. Place the greatest weight on experimental studies of mortality, reproduction, and behavior of animals during and after exposure to methylmercury. These studies should be made on a long-term basis and they should employ exposures that are similar in level to those in the field. There is little merit to working with unrealistically high exposures. Emphasis should be placed on learning what the minimal toxic exposures are and what residue levels they create. These experimental studies, through which lethal, reproductive, and behavioral effects can be related to known exposures and to known residue levels, should be done with representatives of various groups of animals, for marked variation between groups may occur. Priority should be given to species or groups that field studies suggest may be in trouble because of mercury.

6. Seek to learn what histologic and physiologic changes characterize mercury damage in diverse groups of realistically exposed experimental animals. Degeneration of nerve cells, for example, might not be the most important diagnostic feature in the case of invertebrates in which reproduction was blocked. One major objective of this work is to find diagnostic features that can be applied to samples from the field.

7. Determine rates of loss of mercury from the body for many groups of animals. These rates are vital in governing accumulation and toxic effects. It is especially urgent to determine the rates of loss in fish-eating birds and other animals that are suspected of being endangered by mercury. This can be done without sacrificing valuable individuals by using isotopes or properly selected biopsy techniques.

8. Use feathers, hair, eggs, and blood for determinations of mercury content since they can be taken with little or no harm to the animals. The suitability of these substances should be carefully explored, especially for research and monitoring in the field. The use of eggs, for example, would make it possible to conduct extensive surveys, or to make year-to-year comparisons, without killing or capturing animals.

9. Determine whether mercury accumulates in soils or soil organisms---such as grubs and worms--after repeated applications. There is urgent need for this, most acutely where methylmercury seed dressings are used, but also where the more innocuous mercurials, such as methoxyethyl mercury or phenyl mercuric acetate, are used as seed dressings or for other agricultural purposes. There are both practical and scientific reasons for learning whether these compounds accumulate or whether they volatilize and become an insignificant portion of the atmospheric burden of mercury, as has been hypothesized.

10. Investigate natural methylation more extensively. Does it occur in soils as well as in aquatic sediments? Does it occur in living animals to any significant extent? If so, are intestinal microbes responsible or can the body itself produce methylation? In bottom sediments, what conditions control the process? What rates of methylation prevail under different conditions? Is a balance established between methylation and demethylation? Does dimethyl mercury pass promptly from water to air after being formed, or does it remain in solution long enough to be picked up by animals and converted to monomethyl mercury? Are there practicable ways to prevent methylation?

11. Extend the search for mercury contamination to other nations of the world. Study of aquatic systems should include biota and sediment from oceans as well as fresh waters.

FARMING-FOOD-FORESTRY*

The Swedish concern began when the decline in populations of seed-eating birds was attributed to mercurial treatment of cereal seeds for planting. Similarly, declining populations of raptorial birds were attributed to the high content of mercury of their fish prey, due, in part, to contamination of water by mercury used in the pulp and paper industry. Moreover, some Swedish animal-food products showed higher mercury content than did similar products from other countries. These concerns led to extensive investigations and major alterations in agricultural practices and other control procedures.

Agricultural Uses of Mercury

Smart (1968) reported that the pesticidal use of mercury in the world was not less than 2,100 metric tons/year. Of this amount, 1,600 tons were attributed to Japan and 400 tons to the United States.

The value for the United States, reported by Fowler, et al, (1969), included all pesticidal use of mercury. That for agriculture amounted to about 120 metric tons/year, the remainder being used for mildew proofing and for manufacturing paper and pulp and paint.

In seed treatment, dry formulations containing about 1.5% mercury are used. About 25% of cereal acreage is sown with treated seed in Sweden, 35% in Norway, 30% in Finland, and 80% in Denmark. The total area sown with mercury-treated seed in Scandinavia and Finland amounts to about 2 million hectares. The acreage sown with mercury-treated seed in Sweden has dropped sharply since the use of methylmercury was stopped in 1966. About 80% of the cereal seed used in 1960 was treated with mercury. In 15 European countries with a total tillable area of about 340 million hectares, about 23 million, or less than 7% of the total, was seeded with mercury-treated seed grain in 1965. (Tejning, 1967a). The acreage seeded with mercury-treated seed in the United States and Canada is not known; but, based on the apparent use of mercury for treating seed, it may total more than 10 million hectares.

The use of mercury for treating of cereal and sugar-beet seeds began in the 1920's and was routinely adopted for winter cereals during the 1930's. *Fusarium*, *Helminthosporium*, *Ustilago*, and *Septoria* are among the principal cereal-disease organisms concerned. Bunt, smut, and leaf stripe are diseases controlled by mercury treatment of cereal seed. *Phoma betae* is the pathogen causing black leaf and leaf spot of sugar beets, which is controlled by mercury treatment of seed.

Treatment of seeds is credited with increasing the yield of cereal in Sweden 6% to 16%. Estho (1969) stated that the average increase in

---

*Prepared by T.C. Byerly

yield attributed to mercury disinfection of seed was about 9% for rye, 16% for wheat, 13% for barley, and 6% oats. (Estho, 1969).

Translocation of mercury.--Translocation from treated seed is incapable of producing very high contamination in harvested grain. The 20 ppm which might be present in the seed would be diluted in leaves, straw, and grain. Johnels reported (personal communication) the following amounts of mercury: 150 ng/gm of the coleoptile, 70 to 80 ng/gm of the leaves, and only 10 ng/gm of the grain.

Important translocation, however, may follow foliar application. Foliar mercury treatment for blast has been responsible for a relatively high content of mercury in Japanese rice. Lindberg (1967) reported experimental tests in Louisiana which demonstrated translocation to grain after foliar mercury treatment. Such treatment is not recommended in the United States. Foliar treatment of potatoes for late blight and of apples for scab can lead to small residues in tubers or fruit as a result of translocation. Thus Smart (1964) reported residues of 21 to 32 ng/gm of potatoes sprayed with phenylmercury compared to 5 ng/gm for unsprayed controls. Residues also have been reported in tomatoes, pears, and apples after foliar applications of mercury.

Treatment of seed in Sweden.--The permissible dose of mercury for treatment of seed was cut in half by decree in 1965, and the use of methylmercury was prohibited in 1966.

Currently all persons in Sweden using more than 500 kg of spring-sown cereal seed must have an official permit for mercury treatment of such seed. At Swedish rates of seeding, the accepted amount would be sufficient to seed about 2 hectares of wheat, 3 hectares of barley, or 4 of oats. As a precondition of treatment, cereal seed for spring sowing must be analyzed at an official seed-testing station for incidence of infection with seed-borne pathogens. For lots of seed showing 0% to 15% infection, treatment is considered not needed and no permit is issued. For seed showing 16% to 40% infection, treatment is advised and permitted; for seed showing 41% to 100% infection, treatment is necessary and permitted. No permit is needed for mercury treatment of the seed of winter wheat or rye. Under Swedish conditions, these seeds are presumed to require treatment. Cereal seed for export may be treated without restriction, as may seed for scientific purposes. (Kahre, 1970).

After the banning of treatment of seed with methylmercury, preparations based on alkoxyalkylmercury which could be used in the machines designed for treatment with methylmercury soon appeared. Alkoxyalkylmercury has been used ever since. It is said to be somewhat less phytotoxic than is phenylmercury.

Many farmers, concerned about environmental contamination attributed to the use of methylmercury, stopped mercury treatment of winter-wheat and rye seed after the use of methylmercury was banned. Subsequently, bunt, which had almost completely disappeared, became a serious problem in many fields, and in the fall of 1968, farmers were urged to have their seed treated. Reports for 1969 and 1970 indicate that bunt is again under control.

In Sweden, seed may be treated only by trained, licensed persons, and all mercury treatment must be registered. Registration forms must be submitted for all treated seed used. To control seed treatment and to advise reponsible personnel, officials of the central seed-testing station annually visit each of the more than 900 seed firms which treat seed.

There is some use and testing of a nonmercurial compound, Voronit, a thiuram (tetramethylthiuram disulphide) modified with hexachlorobenzene for seed treatment. More recently, Neovoronit, the same compound modified with dimethyldithiocarbamic acid instead of hexachlorobenzene has shown promise. These products are reported to be somewhat less effective in disease control than are mercury agents.

Apparently, sugar-beet and other seed may be treated without permit.

By strict regulation of seed dressing with mercury, the Swedes have made some progress in the restoration of populations of some seed-eating birds. Their population of rooks is reported to be back to that of pre-methylmercury days. Their rationale of regulation (spring restriction) is applicable to our own Northwest--to North Dakota, to eastern Montana, and to the Canadian prairie provinces, where almost all seeding is spring seeding, and the use of mercury-treated seed coincides with the breeding season of seed-eating birds. In the opinion of some phytopathologists, treatment of cereal seed for spring sowing in the United States is generally nonessential, but failure to treat likely would be followed by excessive losses from disease in years of unfavorable weather.

The seasonal variation in pheasant eggs coincides roughly with the seasonality of seed treatment. Thus, by severe restriction of spring treatment, the first brood of seed-eating birds is removed from risk.

Mercury Contamination of Food

Table 3 summarizes some data from various regions on the mercury content of a number of foods. The high content in rice in Japan is particularly notable in Table 4. Swedish chicken eggs in 1966 contained about 20 ng mercury/gm of egg white. Merganser eggs, on the other hand, contained about 2,800 ng of mercury/gm of egg white, about 99% of which was methylmercury (cf Table 11 & 12, Westöö, G., 1969). Westöö's data (Table 5) also indicate that mercury in muscle tissue and egg white is chiefly methylmercury. In liver, kidney, brain and egg yolk, the proportion of total mercury present as methylmercury varies widely, but in no case does the amount of methylmercury approach that of all forms of mercury together.

Jervis and coworkers (1970) reported on the mercury content of several fresh water fishes and of meat, wheat, and milk powder. Several of the reported values exceed 200 ppb.

TABLE 3. MERCURY IN FOODS

Food	Country	ng/g - Range
Haddock*	United States	17 - 23
Herring*	Baltic states	26 - 41
Apples*	United Kingdom	20 - 120
Apples*	New Zealand	11 - 135
Pears*	Australia	40 - 260
Tomatoes*	United Kingdom	12 - 110
Potatoes*	United Kingdom	5 - 32
Wheat*	Sweden	8 - 12
Rice*	Japan	227 - 1000
Rice*	United Kingdom (Imports)	5 - 15
Carrots+	United States	20
White Bread+	United States	4 - 8
Whole Milk+	United States	3 - 10
Beer+	United States	4

* Smart, NA. (1968)

+ Goldwater, LJ. (1964)

Table 4 Mercury Residues in Grain and Fruit Untreated and Treated With Phenyl Mercury Foliar Spray*

Commodity	Mercury, ppb	
	Untreated	Treated
Rice	20 to 100	100 to 700
Mandarin orange		
Skin	10 to 50	30 to 240
Pulp		10 to 40
Apple		
Skin	10 to 50	70 to 310
Pulp	10 to 50	30 to 130

* Mouyu S, and Suwanai M, 1962.

Table 5. Methylmercury in Relation to Total Mercury in Some Swedish Animal Products

Product	Year	Samples	Average level of methylmercury, ng/g	Percent of average level of total mercury
Pork Chop	1968	9	11	97
Pig's liver	1966	3	88	73
Pig's liver	1968	15	16	65
Pig's kidney	1968	21	14	41
Pig's brain	1968	6	1	26
Beef fillet	1966	1	68	92
Beef liver	1968	10	1	23
Calf's liver	1968	13	3	--
Reindeer saddle	1968-69	9	8	86
Reindeer liver	1968-69	27	4	5
Reindeer kidney	1969	10	2	1
Hen's egg, white	1966	6	21	92
Hen's egg, white	1967-68	24	11	91
Hen's egg, yolk	1966	3	8	91
Hen's egg, yolk	1968	6	1	26
Merganser's egg, white	1969	9	2,750	99
Merganser's egg, yolk	1969	9	340	60
Pike and perch	1968-69	300	(0.04 to 8,400) range	99

*Westöö (1969), Table 15.

The Committee is informed that checks of these analyses in another Canadian laboratory failed to confirm such high values, nor are they consistent with other reported values cited in this report. (Jervis et al, 1970).

Recently high levels of mercury (up to 1 ppm) have been found by FDA in tuna muscle; the source of mercury is not known.

Westöö's data (Table 6) clearly show that the mercury content of Swedish pork, beef, and eggs has dropped since the use of methylmercury as seed dressing was stopped. Current values are about the same as those for Danish products.

In addition to the continuing apprehension over mercury-contaminated fish, there has been concern over contaminated meat and eggs from chickens fed mercury-treated seeds. This has led to some experimental work.

Hens were fed experimentally with alkylmercury dressed seed. On a sole diet of such seed, with a mercury content of 15 to 20 ppm, hens lived for 35 to 50 days. At the end of the period, their livers contained 55 to 110 ppm of mercury (Borg et al, 1969).

Tejning and Westerberg (1964) reported that a hen fed alkylmercury treated grain containing about 14 ppm of mercury for 4 1/2 months had about 15 ppm of alkylmercury in breast muscle and 42 ppm in liver. Another hen fed grain containing about 3 ppm of alkylmercury for a year had less than 1 ppm breast muscle and liver. This hen had continued to lay and the eggs contained about 20 ppm of mercury in the whites and about 10 ppm in the yolks. Both hens were apparently healthy.

Tejning (1967b) reported extensive experiments on the effects of feeding methylmercury to hens. He fed various levels--up to about 9ppm in the feed. Hens which received 4.4 ppm of mercury in their feed laid normally throughout the 88-day experimental period, but hatchability was only about 16% compared to 60% for the controls. Egg production and hatchability both declined in the hens fed 9 ppm of mercury in their feed. After 30 days of feeding at this highest level, whites of eggs produced contained about 25 ppm of mercury, yolks only about 2 ppm.

Two hens and one cock developed neurotoxic symptoms after about 67 weeks of being fed feed contaminated with mercury. At autopsy, their brains contained 14.2, 9.8, and 15.3 ug of mercury/gm of wet weight, values comparable to those of mammals showing neurotoxic evidence of mercurial poisoning.

Smart and Lloyd (1963) fed wheat dressed with methylmercury dicyandiamide to hens. After 4 weeks, their eggs contained 8 ppm of mercury, 75% of which was in the egg white. Muscle contained about 4 ppm, liver more than 8 ppm, and kidneys about 8 ppm after 8 weeks of feeding. The laying and general health of the hens were normal and lesions attributable to mercury were found at autopsy. (Smart and Lloyd, 1963.)

The chicks hatched from eggs laid by hens fed high levels of mercury were killed at 5 weeks of age. Presumably they contained about 10 ug of mercury/gm at hatching time. When they were killed, their organs contained less than the amount detectable by the analytical method employed--that is, less than 0.4 ng/gm (Tejning 1967a or b).

Table 6 - Total Mercury Content of Certain Scandinavian Animal Food Products*

Food Product	Total Mercury, ng/gm wet weight			
	1964 through 1966		1967 through 1969	
	Range	Average	Range	Average
Sweden				
Pork chop	16 to 130	30	1 to 16	8
Pig's liver	14 to 180	60	3 to 49	21
Beef filet	2 to 74	12	1 to 5	2
Hens' egg	15 to 43	29	4 to 23	9
Reindeer	5 to 23	13	4 to 17	11
Reindeer liver	9 to 44	26	17 to 270	98
Pike	...	...	40 to 8400	...
Crayfish	...	...	210 to 500	...
Denmark				
Pork chop	2 to 7	3	1 to 8	3
Pig's liver	5 to 20	9	3 to 28	9
Beef filet	2 to 4	3	2 to 8	5
Hen's egg	...	...	5 to 70	14

* Westöös, G. (1969) Table 13.

It is apparent that levels of mercury intake consistent with no apparent disease can lead to hazardous levels of mercury in meat and eggs and that such levels impair hatchability of the eggs. On the other hand, survivors from eggs that hatch show only traces of mercury after some weeks.

Forest Products

Approximately 140 tons of mercury have been dispersed in lakes and streams in Sweden due to the use of mercurial compounds in pulp and paper manufacture. Much of the material rests below mill sites where it is bound to sediments, especially to organic fiber-pulp residues. They may release mercury into the water for many years.

In areas where new organic materials cover the old, oxygen requirements of decay processes may maintain anaerobic conditions in the old sediments. This would minimize the release of mercury. As old mercury-containing sediments were buried more deeply, release of mercury would cease.

Use of mercury in the manufacture of pulp and paper amounted to about 300 kg as phenylmercuric acetate in 1958, according to Halldin (1965). Usage increased to a peak of about 24,000 kg in 1960. Voluntary restriction of such use occurred from 1962 to 1965, inclusive. Usage was banned as a slimicide about 1966 and as a wet-pulp preservative about 1967.

The paper and pulp industries now use pentachlor phenolic compounds and polybrome ketone compounds as slimicides. Some fish kills have been attributed to polychlorophenols.

The pulp industry has shifted from wet to dry pulp thus achieving savings in cost concomitantly with the forced abandonment of the use of phenylmercury.

Fungicides are still needed by the lumber industry to prevent a condition described as "blue stain." Presumably, polychlorphenolic compounds are used to prevent the condition.

Among 60 locations at which fishing has been banned because of a high mercury content of the fish, 19 are pulp or paper locations and 5 chlor-alkali locations. Four of the chlor-alkali plants are also pulp or paper-mill sites.

Nonfood Use

Little heed is given nonfood sources of mercury which may affect man. Goldwater (1964) lists some of the nonfood products containing mercury as follows: "Phenylmercury antifungal agents are now being

added to various paints to act as preservatives. A similar use of mercury is made in floor waxes, furniture polishes and fabric softeners. Commercial laundries use phenylmercurials to suppress mildew and cautious couples use them to suppress pregnancy. Less obvious is the use of mercury in tooth brushes and air conditioner filters."

Regulation

Pesticide Use.--Regulation of pesticide use in Sweden is the responsibility of the National Poisons and Pesticides Board, an autonomous affiliate of the Ministry of Agriculture. The Board requires submission of data on efficacy and toxicity of candidate products.

Pesticides are defined by the Board as products meant to be used for protection against pests, including those--for example, phenylmercury--used in industry. Pesticides must be registered by the Board. Registrants must provide information on the effects of the product on man, domestic animals, beneficial insects, wildlife, and the environment.

The Board, which can prevent the use of dangerous pesticides, evaluates the risks and benefits of using a given pesticide in determining whether or not to permit its use.

Permitted products are classified as follows:

1. High risk. Such products must be licensed by the Poisons and Pesticides Board. These may be used only by trained, licensed applicators.

2. Great risk. (but less risky than Class 1). Such products must bear appropriate directions and warnings on the label. In general, this class would include products with an LD_{50} of 200 to 900 mg/kg of body weight of the test animal.

3. General use. Products in Class 3 include those with an LD_{50} of more than 1,000 mg/kg of body weight of the test animal.

Pesticide Disposal.--Sweden has initiated a semistate system of collecting, recycling, and salvaging unused pesticides. Remnants are brought to a community collection center and then transported to the salvage center, "Savlab." Paper sacks have been designed so that the opening is destructive, thus preventing re-use.

Food Laws.--Food-law supervision in Sweden is the responsibility of the National Veterinary Board, an autonomous affiliate of the Ministry of Agriculture. Food additives are controlled by the Board of Commerce and occupational health matters in food establishments by the Board of Health and Social Welfare. The Board of Commerce has established tolerances for residues of a few pesticides in foods. The tolerances for fruits and vegetables are listed in Table 7.

With respect to restriction of commercial fishing, the Veterinary Board, in conjunction with the Board of Health and Social Welfare, issues restraining orders, designating water areas where fish are considered unfit for human consumption because of the content of mercury.

Table 7. Tolerances of Pesticide Residues in Foods

Pesticide	Permitted Residue in food, ppm	
	General	Special
Aldrin	0.1	0.05 in carrots
Dieldrin	0.1	0.05 in carrots
DDT	1.0	2.0 in pears and apples
Ethron	0.5	1.0 in pears and apples
Lindane	1.0	1.0 in pears and apples
Parathion	0.05	1.0 in pears and apples

Decisions of the Veterinary Board are not reviewed by the Ministry of Agriculture. Decisions of the Board are assumed to rest on competent professional evaluation of relevant information. Decisions of the Board may be appealed to the Government--that is, to the "King in Council" or finally to the Supreme Administrative Court. Apparently appeals are unusual.

General.--A new environmental protection law became effective in Sweden in 1969. It established an Environmental Franchise Board. The law covers the use of real estate in any manner resulting in pollution of water, air, or in environmental "pollution" through noise, vibration or light, which is not wholly temporary. Operating licenses or dispensations must be obtained for operations which will disturb the environment. (Svensfor 1969).

Supplementary Comments on Finland

Finland followed Sweden's lead and stopped the use of alkylmercury for treatment of cereal seed in early 1966. Use of alkylmercury for this purpose in Finland has not been general. Principal seed disinfectants were two alkoxyalkyl compounds. Nor were there reports of damage to seed-eating birds and their predators in Finland.

There was public concern over the possible contamination of hens' eggs through feeding hens grain from treated seed. Substantial tests were conducted to settle the point. Eggs produced by hens receiving about 15 ppm of alkoxyalkylmercury in their feed reached levels as high as 3 ppm in the 10th week of such feeding. Mercury was principally in the yolk, not in the albumen as Swedish workers had found after feeding alkylmercury-treated seed (Tuomisto, et al., 1968).

The use of mercury in Finland was formerly about 50 tons/year, an estimated 9 tons escaping into water. Chlor-alkali plants used about 32 tons, pulp and paper manufacturing about 10 tons as slimicide, and agriculture about 4 tons. The pulp and paper industry reportedly has stopped using mercury; thus, the current loss to water is probably only about 4 to 5 tons/year.

The Finns found that it was not possible to protect oats against loose smut nor barley against leaf stripe nor cereals generally against Fusarium, when the seed treatment rate with alkoxyalkyl mercury was cut in half (from 200 to 100 gm/100 kg of seed with a 1.5% dust.)

We were told that restricting fresh-water fishing to areas in which food fish contained less than 1 ppm in their flesh would reduce Finnish production of such fish by about 7%. There may be 100,000 Finns in these areas who are sufficiently heavy eaters of fish to represent a population at risk.

Summary of Findings

1. Sweden has eliminated the use of alkyl(generally methyl)mercury for treatment of cereal seeds.

2. Sweden has eliminated the use of mercury as a slimicide and as a pulp preservative.

3. Sweden has reduced the use of mercury for treating seed (alkoxyalkylmercury is now used for this purpose) to about one fourth of the 1960 level.

4. Residues of mercury in Swedish animal-food products have been reduced.

5. Residues of mercury in pike have apparently been reduced at some locations.

6. The populations of seed-eating birds have been restored.

7. Alternate nonmercury fungicides have been introduced without full evaluation of the risks and benefits of their use.

8. The risk of loss of yield and quality of cereal grains has increased.

Recommendations

1. Eliminate the use of alkylmercury compounds as pesticides.

2. Restrict the use of aryl- and other nonalkylmercury pesticides for such uses as are necessary on the basis of demonstration of hazard from phytopathogens against which these mercurials provide the only effective means of protection.

3. Evaluate risks and benefits of substitutes for mercurial slimicides and algicides.

4. Restrict all industrial uses of mercury to conditions which will minimize contamination of water and land.

5. Initiate, in cooperation with industry and the states, a salvage program for unused mercurial and other pesticides.

6. Systematically survey food products in addition to fish for total content of mercury and methylmercury.

CHAPTER 6

AIRBORNE MERCURY*

Occurrence of Mercury in the Atmosphere

Very little is known about either the quantitative or qualitative aspects of mercury in the atmosphere, since only a few measurements have ever been made of mercury concentrations in the air. The Swedish literature generally cites work done in Germany in the early 1930's (Stock and Cucuel, 1934) which gives an average value of 0.02 $\mu g/m^3$ of total mercury in air. Some measurements in the United States (Cholak, 1952) gave values for particulate mercury ranging from 0.01 to 0.21 $\mu g/m^3$.

High-sensitivity measurements of mercury vapor (efficiency of particle removal not specified) were carried out for 2 years in the San Francisco Bay area (Williston, 1968). Seasonal trends were noted, the winter values ranging from 0.001 to 0.025 $\mu g/m^3$ and summer values from 0.002 to 0.050 $\mu g/m^3$. Williston attributed the variations to temperature and moisture in the ground with more volatilization, possibly being associated with warming and drying of the soil. He also suggested an association with smog, since he found levels in the range of 0.005 $\mu g/m^3$ on smoggy days contrasting with perhaps 0.003 on normal days.

Neither Sweden nor Finland has yet begun to monitor atmospheric mercury, although such monitoring is in their plans for the future (Larsson, 1970). So far, difficulties in measurement and instrumentation have prevented large-scale monitoring of mercury in air.

In addition to the paucity of measurements of the concentration of mercury in air, we know practically nothing about the chemical and physical forms of mercury in the atmosphere or of their transformation therein.

Sources of Atmospheric Mercury

The mercury may occur as a vapor or as an aerosol or both. It may also be present as organic or inorganic mercury. Both dimethyl mercury and elemental mercury are quite volatile at ordinary outdoor temperatures.

Certain Swedish scientists think that much of the atmospheric mercury is in the form of vaporized dimethyl mercury and that it reaches the air primarily through evaporation from soil or water. However, both monomethyl and metallic mercury are also volatile. Nothing is known about the stability of organic mercury in the atmosphere.

---

*Prepared by J. E. Thompson

Emissions of mercury to the atmosphere by industrial sources, such as chlor-alkali plants, are not well quantified at present, but it is quite likely that most of such mercury is emitted as elemental mercury vapor or aerosol--as much as 10 gm/hour having been estimated to arise from a single chlor-alkali plant (Eriksson, personal communication).

Transport of Mercury in the Environment

The mercury levels of fish in several Swedish lakes showed relatively high values, although there were no known industrial discharges of mercury into the lakes. Since these lakes are near industrial sources which emit mercury to the air, it is conjectured that the mercury comes primarily from the atmosphere. (Johnels, et al., 1968). Johnels and Eriksson (personal communication) suggest also that interruptions of atmospheric exchange can lead to higher than normal accululation of mercury in acid lakes (see chapter 2).

In Finland, there are also some remote lakes with no known sources of industrial water contamination, where relatively high levels of mercury are found in the fish. It was suggested in this instance (Miettinen, personal communication) that runoff water from the surrounding soils or mineral deposits is the principal source of mercury. Little or no data are available to support the explanation in either the Swedish or Finnish case, but both are plausible.

Although the role of the atmosphere in global and regional transport of mercury is largely unknown, it is possible to construct a partial model of the movement of mercury among the air, soil, and water components of the environment. Such a model is depicted in Figure 2. A similar model has been proposed by Eriksson (unpublished data) to illustrate the budget of mercury in the soil as it related to the atmosphere and runoff. This budget (Table 8) assumes that there are 1,000,000 mg/hectare (ha) in soil to a depth of one meter (70 μg of mercury/kg in soil and 1,000 μg/kg in organic matter in the soil). It also assumes a concentration of 0.02 μg Hg/m^3 in the air near the ground (Stock and Cuecel, 1934).

Eriksson estimates the atmospheric burden in the air column located above one hectare as 2,000 mg/ha. This would project to a global atmospheric burden of about 80,000 metric tons. This can be viewed in relationship to the total estimated annual use of mercury throughout the world, about 10,000 tons, of which only a portion (unknown) reaches the atmosphere.

Eriksson's model is an interesting and important one; however, it may be in gross error quantitatively, since we have only very rough estimates of atmospheric mercury concentrations.

Monthly concentrations of total mercury in precipitation samples were measured at Stromsardt in Central Sweden at one site during 1969 and 1970. The 1969 data show rather wide seasonal changes, relating to evaporation during warm summer months, with the lowest values occurring during winter and the highest values in summer. A low of 0.08 μg Hg/liter was recorded for December and a high of 1.45 μg Hg/liter in July.

Figure 2. Mercury Cycle in the Environment

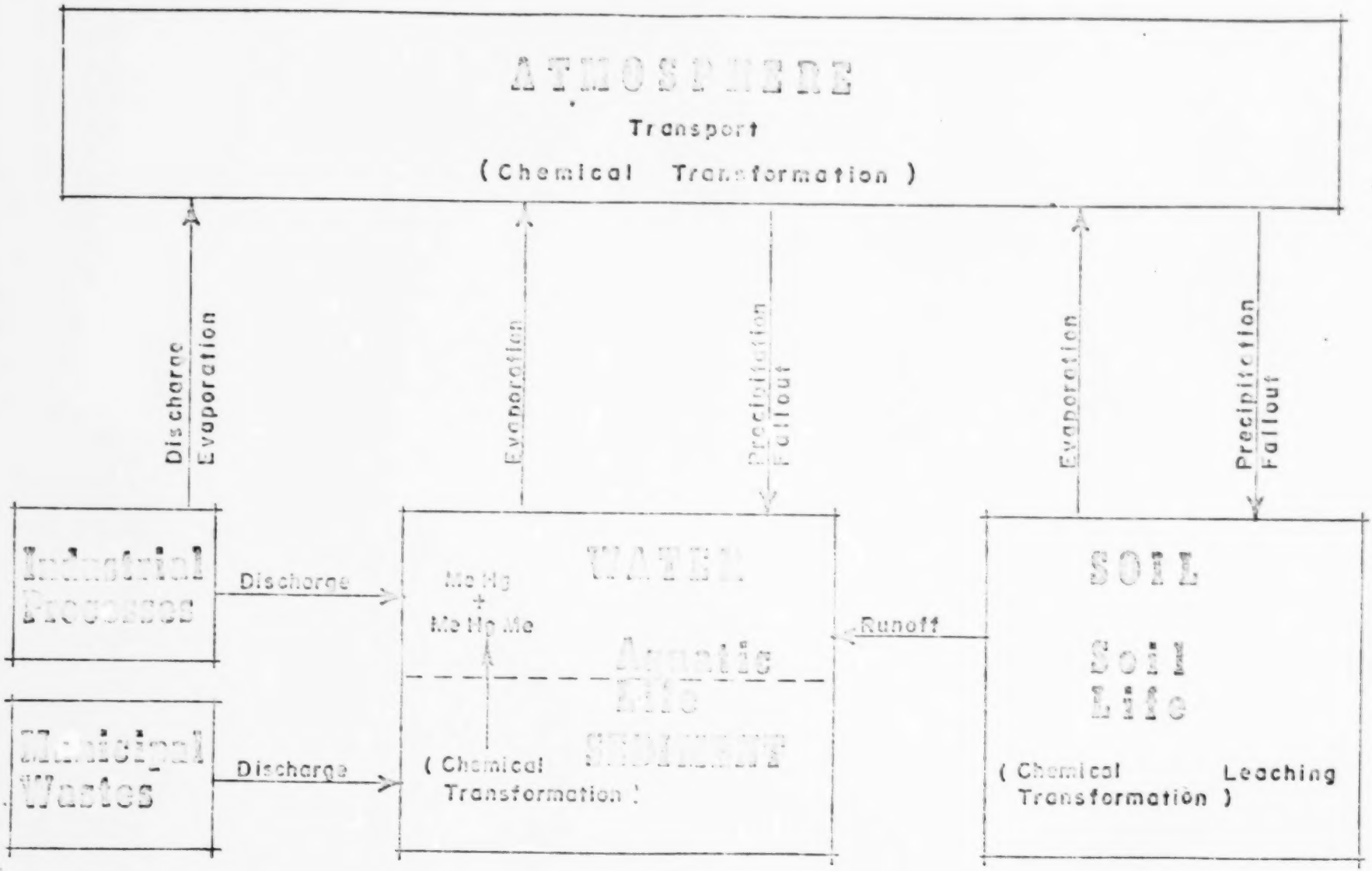


TABLE 6 ANNUAL MERCURY BUDGET

Environmental component	Amount of mercury, mg/hectare
Soil to depth of 1 meter	1,000,000
Precipitation (annual addition to soil)	5,000
Runoff (annual loss from soil)	500
Evaporation (annual loss from soil, addition to atmosphere)	4,500
Atmosphere	2,000*

*Amount of mercury in entire air column over one hectare of soil.

The annual mean is about 0.5 ug/liter. These data, not yet published, are based on a personal communication from Professor Erik Eriksson of the Swedish Meteorological Institute. These results support the observations of Williston already mentioned. Apparently, the higher summer temperature would encourage evaporation of volatile mercury (metallic, methyl, and dimethyl) from soil and water, thus providing more mercury available in the atmosphere for rainout.

Conclusions and Recommendations

The levels of atmospheric mercury in the United States (0.001 to 0.21 $\mu g/m^3$) which have been observed from the very limited ambient air sampling are well below the threshold limit values of 0.1 mg/m^3 for metallic vapour and inorganic compounds and 0.01 mg/m^3 for organic mercury. Thus it would appear that unless a large increase in the level of atmospheric mercury occurs the health hazard from airborne mercury would be relatively insignificant compared to that from eating contaminated food.

Nevertheless, there is so little known about mercury in the air that it behooves us to develop a much more acute scientific awareness of the situation. We also need a more accurate basis for calculating the total body intake of mercury by human beings from all sources, including the atmosphere.

The following specific recommendations for further research are based on the gaps which must be filled in order to properly delineate the role of airborne mercury in environmental contamination:

1. Determine the chemical and physical forms of mercury in the air both near to and remote from known sources.
2. Determine the quantitative and qualitative aspects of transformations of mercury and its compounds in air and the controlling circumstances.
3. Determine chemical or physical forms in which mercury is emitted to the air from soil, water, vegetation, and man-made sources; how much is emitted from each source; and which are the significantly large sources.
4. Determine a total budget for the environmental distribution of mercury, including sources, transport, transformation, deposition, and fate.

ANALYTICAL METHODS*

"The analysis of biological materials for traces of mercury (one part per million or less) is a difficult and complicated subject. It requires experienced, capable people with good facilities." This was the statement made to the U.S. study group at the beginning of a meeting with the Swedish Committee for Toxicological Evaluation of Hazards from Mercury in Fish, by Dr. Maths Berlin of the University of Lund, a member of the Committee. It remains applicable in Sweden after many years of work, and also applies with equal force to our own experience in the United States thus far.

Clearly, reliable chemical analyses are essential prerequisites to the success of any effort aimed at a fundamental understanding of the hazards posed by mercury in food and in the environment or aimed at protection of the public health against such hazards. For regulatory purposes, including legal actions, the sensitivity needed is at least 0.1 ppm,† with an accuracy well established quantitatively--if possible, to within ± 10%. For research purposes, such as determining the distribution of mercury in the tissues of small experimental animals, it may be necessary to accept less accuracy in order to achieve a sensitivity of at least 0.01 µg on an absolute basis, equivalent to 0.01 to 0.001 ppm for sample sizes of 1 to 10 gm. The types of analytic methods available are determined by the chemical properties of mercury and its compounds, as follows.

Analytical Characteristics of Mercury

The ease of volatization of mercury and many of its compounds is a striking feature. On the one hand, this requires that care be taken to avoid losses; on the other hand, it makes possible some novel procedures in which, for example, the elemental mercury in an aqueous medium (resulting from appropriate treatment of the sample) is rapidly separated from other substances by a stream of air bubbled through the medium. The amount of mercury vaporized into the air stream is then measured by flameless atomic absorption. The high vapor pressure is beneficial also for another kind of analytic method, the gas chromatographic determination of methylmercury compounds (the form in which mercury exists in fish) and other organomercurials.

However, the high volatility requires special precautions in handling, to avoid escape of organomercurial compounds from many kinds of samples, and is partly responsible for the serious analytic errors sometimes encountered because of loss of methylmercury in procedures involving the hot-acid digestion of samples, when inefficient reflux condensers or incautiously high temperatures are permitted.

Another characteristic of mercury is its strong affinity for sulphur compounds. This has been used to good advantage in the spectrophotometric determination of submilligram quantities of mercury by means of the dithizone complex, which was the best method available until 6 or 8 years ago. It is used also in the Westoo gas chromatography procedure (Westoo 1967) for separation of methylmercury from interferences by complexing with cysteine.

---

* Prepared by Alfred Weissler

† See discussion of units for reporting concentrations of mercury in Appendix C.

In addition, the high reactivity of mercury with sulfhydryl groups in enzymes and other biomacromolecules appears to be involved in the mechanism of action of mercury compounds on living organisms.

A third analytic property of mercury is that when exposed to neutrons (as in a nuclear reactor) some of its seven stable isotopes are converted into the radioactive species listed in Table 9. Quantitative analysis of the mercury content of a sample then can be achieved by measuring the intensity of the characteristic gamma-ray and X-ray spectrum emitted by any of these nuclides. This procedure is known as neutron activation analysis.

Table 9. Radioactive Isotopes of Mercury and Their Respective Half-Lives.

Isotope	Half-life
^{203}Hg	47 days
^{197}Hg	65 hours
^{205}Hg	5 minutes

Methods of Analysis

Dithizone.--Until 1964, the standard method in Sweden and Finland (as well as elsewhere) for determining small amounts of mercury was by colorimetry or spectrophotometry of the dithizone complex. This method was used, for example, in the early Swedish studies on mercury poisoning in wildlife (Berg, Wannetorp, et al, 1969) and in the Japanese investigations of the Minamata and Niigata incidents, (Irukayama, Kondo, et al, 1961; Tsubaki, Sato, et al, 1967). A typical procedure for the determination of mercury in foods (AOAC Methods of Analysis, 1965) consists of digestion of a 10 gm sample with hot nitric and sulfuric acids under reflux, removal of interferences, addition of dithizone reagent, and spectrophotometric determination of the color intensity of the resulting complex.

However, the dithizone method is relatively insensitive, requiring excessively large samples when levels of mercury are low. In addition, it sometimes gives incorrect results in routine analyses, unless the chemist is experienced and very careful, partly because of losses of volatile, stable methylmercury compounds during the hot-acid digestion. These drawbacks have stimulated a considerable effort, in the United States currently and in Scandinavia and Finland during the past several years, aimed at development of improved analytic methods.

Neutron Activation.--A nondestructive neutron activation method was described by Westermark and Sjostrand (1960), but the sensitivity was limited to about 0.5 ppm in biologic material. In 1964, a great improvement in sensitivity to about 0.001 ppm in an 0.5-gm sample was achieved (Sjostrand, 1964) by introduction of chemical separation steps. Thus, after the neutron irradiation (2 or 3 days at a thermal neutron flux of 10^{12} n/cm^2 per second, the sample is decomposed by boiling with nitric and sulfuric acids in a closed system, and 20 mg of carrier mercury are added as mercuric chloride; then, perchloric acid and glycine are added and the mercury is distilled off at temperatures up to 250° C as a volatile compound. Next, the mercury in the distillate is electrodeposited onto gold foil, the foil is weighed, and the 197 Hg content is determined by gamma-spectrometry with a sodium iodide crystal and 200 channels of a multichannel analyzer, appropriate corrections being made for the percent recovery of the added carrier. This method has a precision and accuracy of about ± 2%, and is generally regarded in Sweden as the preferred method for determining total mercury in biologic samples. (Greater sensitivity is possible through use of a higher neutron flux.)

The capacity to perform about 8,000 analyses per year exists in Stockholm, at a cost of about 20 dollars per sample. A similar analytic service is commercially available in the United States, at a cost of about 35 dollars per sample (Gulf General Atomic, 1969). Neutron activation analyses for mercury are also available elsewhere as at the AEC Idaho Falls laboratory which uses much higher neutron fluxes, high resolution Ge(Li) detectors,

and sophisticated accessory equipment. For the future, a possible simplified technique may make use of californium-252 as the neutron source, eliminating the need and expense of a nuclear reactor.

In Finland, neutron activation analysis is also much used for mercury determinations. One recent method (Häsänsen, 1970), which employs a simple separation of the activated mercury plus carrier onto copper powder, has given good results in the routine analysis of 700 fresh biologic samples at levels down to 0.002 ppm.

Another successful procedure, from Yugoslavia (Kosta and Byrne, 1969), involves neutron irradiation followed by combustion of a 50-mg sample in a stream of oxygen at 600° C in a silica tube, removal of interferences by silver-impregnated silica wool at 300° C, selective trapping of mercury on selenium-impregnated paper at 100° C, and counting of the ^{197}Hg content of the paper; this is a rapid method, with a reported sensitivity of 0.001 mg.

Gas Chromatography.--An important Swedish contribution to the analytic chemistry of mercury has been the identification (Westöö, 1966) of methylmercury as the predominant form of mercury in fish and some other animals, followed by her improved gas chromatographic procedures (Westöö, 1967, 1968) for the determination of methylmercury in a wide variety of biologic materials at a sensitivity approaching 0.001 ppm in favorable cases. In view of the special toxicologic significance of methylmercury, this method has the advantage of differentiating among compounds of methylmercury, ethylmercury, and methoxyethylmercury (which each give separate peaks), phenylmercury (which gives a peak at a much longer retention time), dimethylmercury (which reportedly gives no response on the electron-capture detector used, but can be converted into methylmercury halide for quantitation), and inorganic mercury (which is not measured at all). The need for such differentiation is clear from the fact that the environment may contain any or all of these forms of mercury as a result of industrial wastes, seed treatment with various types of organomercurial fungicides, slime control by mercury compounds in paper-pulp factories, use of phenylmercuric acetate as a preservative in some cosmetics, and so on.

Several laboratories in the United States and Canada are now engaged in determining methylmercury by gas chromatography, and some variations in procedure have already been suggested. The technique used at the Food and Drug Administration, after personal consultations with Dr. Westöö concerning manipulative details (oral communication, July 28, 1970) and generally based on her procedure, has given good results. It consists of homogenization of a 10-gm sample of fish with water in a blender, addition of concentrated hydrochloric acid, and extraction of the methylmercury chloride into benzene. Separation from interferences is achieved by complexing with aqueous cysteine acetate making the solution strongly acid with hydrochloric acid, and re-extracting into a small volume of benzene. After drying, an aliquot of the benzene solution (about 5 µl) is injected into the gas chromatograph column of Carbowax 20 M on Chromosorb W operated at 180° C; the peak height recorded at the correct retention time shows the methylmercury content.

Gas chromatography has been used in Sweden for extensive surveys of mercury contamination (Westöö, 1969) and (Westöö and Rydalv 1969) at a cost of about 12 dollars per analysis.

In experienced hands, the precision is about 12% and the reliability is 20% or better when calibrated by standards run through the entire procedures. Some modifications of the extraction and cleanup steps, using methylmercury bromide instead of the chloride, have been proposed (S. Jensen, personal communication, August 19, 1970; Rudling, 1970).

Atomic Absorption.--The third major analytic technique used in Scandinavia is atomic absorption (AA) which measures the total mercury content. This is a relatively simple, rapid, and inexpensive method which has attracted interest in many countries. It is based on conversion of all the mercury in the sample into elemental mercury vapor, by appropriate chemical treatment, and determination of the amount present by measuring its absorption of radiation from a mercury lamp, either at room temperature or else in the more conventional flame-atomic-absorption apparatus. A sensitivity of 0.01 µg is readily attained, but the precision and accuracy are only moderate.

A convenient and simple AA procedure (Brandenberger and Bader, 1967) is used in Dr. Neittinen's laboratory in Helsinki. A 1-gm sample is burned in oxygen in a large closed flask, the products are absorbed in dilute acid, and the mercury is electrodeposited out of the solution onto a copper wire. The wire is then inserted into the side arm of a 15-cm optical absorption cell and heated electrically to liberate its mercury as vapor, which is then quantitated by flameless atomic absorption.

In Sweden, Lidgren & Ulfvarson (1968) also use oxygen to burn the sample, but in a combustion train in which the gases pass through sodium carbonate at 200° C and then over gold foil to collect the mercury. After combustion is complete, the gold is heated rapidly to dull redness, and the mercury vapor thus released is determined by flameless AA in a 10-cm cell, at a reported sensitivity of 1 ng.

For the analysis of mercury in rocks, at the Royal Institute of Technology in Stockholm, I. G. Andersson (personal communication, 1970) has developed a double-beam AA instrument with a sensivitity of about 0.1 ng achieved by the use of a 100-cm optical path and unfiltered mercury light (instead of the usual 253.7 nm monochromatic radiation). An induction furnace volatizes mercury vapor out of the rock sample into an air stream. This stream is split into two equal parts; one passes through glass wool into one of the optical cells, and the other passes through gold-impregnated glass wool (to remove the mercury) into the other cell. The mercury content is measured by the difference between the light absorption in the two cells, which thus avoids errors due to light-absorbing interferences. About 30 samples can be analyzed per hour, with accuracy and precision of better than 10%.

At the National Institute of Occupational Health in Stockholm, G. Lindstedt (1970) uses an automated AA method which can analyze urine samples at the rate of about one per minute, with a sensitivity of 0.002 ppm in a 1-ml sample. The samples are digested overnight with potassium permanganate-sulfuric acid at room temperature, then treated with stannous chloride to reduce mercury compounds to elemental mercury which is vaporized into an air stream passed through the solution, and determined by flameless atomic absorption using the 253.7 nm line. This procedure also has been adapted for the analysis of fish tissue and blood.

In North America, many varieties of atomic absorption methods are in use for mercury (personal communications; see also AOAC 1970) by workers such as J. A. Wenninger of the United States Food and Drug Administration; E. F. Dalton of the United States Department of Agriculture; M. Malaiyandi of the Ottawa Experimental Farm; V. A. Thorpe of the Michigan Department of Agriculture; V. A. Stenger and D. J. Peterson of Dow Chemical Company; R. E. Christensen of the Wisconsin Alumni Research Foundation; and W. L. Hoover of Texas A. and M. University. The experience with these methods has been generally good, but care must be taken to avoid losses of volatile mercury compounds during the initial digestion of samples with hot acid.

Results of a very recent collaborative study of an AA procedure within the Food and Drug Administration showed recoveries in the range of 80 to 90% in nine different laboratories (Glover and Holland 1970). A related method (Wenninger 1968) which uses direct pyrolysis of the sample followed by AA (thus avoiding the acid digestion) holds some promise for development as a rapid inexpensive screening method for mercury, at a sensitivity of 0.01 ppm and a precision of about ± 20%.

Another analytic tool is the use of radioactive mercury isotopes, particularly ^{203}Hg. This has been valuable in an automated method by radioisotope dilution (Sullivan and Lenz, 1969), in localization of the tissue and cellular distribution of mercury by autoradiography (Bächstrom 1969) and in studies of metabolic fate and biologic half-lives of methylmercury (Miettinen et al, 1969) (Östlund 1970).

Other techniques which may be applicable to current problems in mercury analysis are x-ray fluorescence and the polarography of organomercurials.

COMMENTS

Sample Homogeneity: It is well known that quite different concentrations of mercury are found in the various internal organs, being concentrated to some extent in kidney, liver, and brain. For this reason, in Scandinavia and Finland, the analysis of fish as food is performed on a sample of the edible portion only, the fillet of muscle tissue without bones, scales, skin, viscera, head, or tail.

There still remains the question of possible inhomogeneity of the mercury distribution within the muscle tissue, which could lead to incompatible results in replicate analyses or comparative analyses of the same fish by different laboratories. In Sweden, extensive experiments by Westöö (Personal Communication, August 21, 1970) have shown that there is no significant inhomogeneity in northern pike which is the standard indicator fish; nevertheless, the analytic samples are taken from a specified region of the dorsal muscle. In Finland, Miettinen (Personal Communication, August 24, 1970) reported that he has found variations of up to 30% in the mercury content of muscle in a study of various animal species.

For public health purposes in the United States, a safe sampling procedure would be to homogenize the entire fish fillet thoroughly after careful cleaning, until such time as uniformity of mercury content in the muscle tissue is demonstrated for those species which are of importance in our country.

Water and Air Analysis: In Scandinavia there has been relatively little emphasis on mercury determinations in water and air. Consequently, more remains to be done on methods development in this field than in that of food analysis.

For water analysis, the dithizone method has been used by some laboratories in the United States. However, heavy metals other than mercury also give a positive result; furthermore, the method responds only to mercuric ion, not to organomercurials. It would be very desirable for some purposes to have analytic methods which distinguish among the various chemical forms of mercury in water. The greatest need, however, is for a rapid method for measuring the total amount of mercury in water at levels down to 1 part in 10^{12}.

For analysis of air, it is useful to determine both mercury and its compounds in vapor and particulate forms. A reasonable approach is to draw a large metered volume of air first through a fine filter to retain the particles, measuring the atomic absorption at 253.7 nm due to elemental mercury in the particle-free air and then through sulfuric acid potassium permanganate solution to retain the mercuous mercury fraction. Each fraction could then be analyzed separately by one of the methods described earlier. Again, a high sensitivity is needed, at least 0.001 $\mu g/m^3$ of air.

SUMMARY OF FINDINGS

1. Good methods have been developed in Sweden, Denmark, and Finland for the analysis of fish, other foods, and body tissues for total mercury by neutron activation analysis and atomic absorption and for methyl mercury and other organomercurials by gas chromatography.

2. These methods have been used successfully for extensive surveys of the extent of mercury contamination in Scandinavia and Finland in order to determine the magnitude of the public health hazard.

3. As a result of intensive developmental effort and extensive experience, the analytic methods for mercury used in Scandinavia and Finland are more sensitive and reliable than are those of many laboratories in the United States.

4. The analysis of air or water for minute traces of mercury has been given less attention.

RECOMMENDATIONS

1. Increase American adaptation and use of recent Scandinavian procedures for the determination of submicrogram amounts of mercury.

2. Review the current official methods used in the United States for the analysis of mercury in fish and other foods. Sampling techniques and possibly inhomogeneous distributions of mercury in edible tissues are among the areas which need attention.

3. Develop improved analytic methods to distinguish and measure methylmercury, phenylmercury, dimethylmercury, methoxyethyl mercury, other organomercury, and inorganic mercury compounds, for use in specialized studies.

4. Provide rapid and sensitive screening methods for surveillance of mercury levels in foods and in human populations (blood and hair). Atomic absorption is the most promising technique for this purpose.

5. Develop improved methods for the determination of very small concentrations of mercury and its compounds present as vapor and in particulate forms, in air, at a sensitivity of at least 1 ng/m^3 of air.

6. Develop improved methods for the analysis of mercury in the water environment and in waste discharges to the water environment. The needed sensitivities are 1 ng/liter in water, 0.1 ppm in bottom sediment on a dry-weight basis, and 0.01 ppm in aquatic life on a wet-weight basis.

7. Increase uniformity of usage of units for reporting mercury concentrations.

8. Establish firmly the reliability and compatibility of the analytic results from different laboratories. The validation system should include collaborative studies of methods and equipment, the exchange of standard samples, and frequent quality-control samples, on a continuing basis.

Appendix A

MEMO
August 17, 1970

MEETING WITH THE EXPERT COMMITTEE FOR TOXICOLOGICAL EVALUATION
[illegible] MERCURY IN FISH and others

Stockholm, Sweden

Introduction

Lars Fell [illegible], M.D., Professor and Chairman
Department of Environmental Hygiene
The Karolinska Institute and the National Institute of Public Health

Film showing incidence in cats of fish contaminated with methyl mercury

Staffan Skerfving, M.D., Secretary
Department of Nutrition and Food Hygiene
The National Institute of Public Health

Fish [illegible] (by invited guest)

Leonard Goldwater, M.D., Dr. P.H.
Mayo Clinic, Rochester, Minnesota

Blood, hair and brain concentration of mercury as indicators of [illegible]

Reliability of available analytical data

Mats Berlin, M.D., Department of Hygiene, University of Lund

Dr. Skerfving

Fredrik Berglund, M.D., Department of Nutrition and Food Hygiene, The National Institute of Public Health

Gunnar Nordberg, M.D., the Karolinska Institute, Department of Environmental Hygiene

Crawford Grant, Vet. M.D., the National Pharmaceutical Laboratory

Appendix A (Cont'd)

Pathology and clinical symptoms in methyl mercury intoxication

Dr. Grant

Ake Svensson, M.D., Department of Medicine, The National Institute of Occupational Health

Discussion

Dose-response relationships in methyl mercury intoxication

Dr. Skerfving

Discussion

Concentration of mercury in blood and hair in normal subjects and in exposed groups without symptoms

Stig Tejning, M.D., Department of Occupational Medicine, Lund Hospital

Discussion

Genetic effects of methyl mercury

Claes Ramel, M.D., Department of Genetics, University of Stockholm

Discussion

Consumption of fish in Sweden

Dr. Skerfving

Discussion

Medical evaluation of risks (acceptable daily intake)

Dr. Skerfving

Discussion

Appendix A (Cont'd)

TUESDAY
August 18, 1970

National Environment Protection Board, Smidesvägen 5, Solna

Chairman

Professor Erik Ekman,
The Swedish Museum of Natural History, Stockholm

Introduction

Lennart Hansen, Ph.D.
Director of Research
Research Council of the Swedish Environment Protection Board

Mercury in Biological Systems

Prof. Jernelöv

Bi- and Dimethyl Mercury

Ulf Olsson, Ph.D.
The Swedish Environment Protection Board

Transport of Mercury in Air

Erik Fredriksson, M.D.
Institute of Theoretical Meteorology
Department of Meteorology
University of Uppsala
and
Meteorological Institute, Stockholm University

Discussion

Mercury in Lake Water and Sediments

Torsten Hasselroth,
Swedish Environment Protection Board
Research Laboratory, Drottningholm

Discussion

Appendix A (Cont'd)

Industrial Mercury Emissions

Anders Kallin
National Environment Protection Board
Water Protection Division, Solna

Discussion

Restoration of Mercury Contaminated Lakes and Rivers

Lars Landner
Swedish Water and Air Pollution Research Laboratory
Stockholm

Discussion

Appendix A (Cont'd)

MERCURY

August 13, 1970

Conference Room, National Institute of Public Health

Determination of mercury by activation analysis

Torbjörn Westermark, Ph.D.
Department of Nuclear Chemistry
Royal Institute of Technology

Determination of mercury in biological materials by atomic absorption

Ulf Ullvarson, Ph.D.
National Institute of Materials Testing

Determination of mercury in minerals by double beam atomic absorption

Lars-Gunnar Andersson

Automated analysis of pollutants by atomic absorption

Gösta Sandstedt, Ph.D.
National Institute of Occupational Health
Dept of Chemistry

Discussion

Determination of methylmercury in biological material by gas-liquid chromatography

Curmel Westöö, Ph.D.
National Institute of Public Health

Alternative method of extraction of methylmercury from biological material

Sören Jensen, Ph.D.
Swedish Environment Protection Board

Determination of methylmercury in organic tissues

Lars Rudling

Appendix 3 (Cont'd)

Discussion

Demonstration of activation analysis at the Isotopes Technique Laboratory.

Demonstration of flame hydride atomic absorption at the Royal Institute of Technology.

Demonstration of the analysis of methylmercury at the National Institute of Public Health.

Demonstration of automated analysis of mercury by atomic absorption at the National Institute of Occupational Health.

Appendix A (Cont'd)

THURSDAY
August 20, 1970

Program arranged by the National Poisons and Pesticides Board

Place: Gamla stadshusberedningen, Konsilhuset, Myntorget 2, Stockholm.

During the meeting there will be a presentation of the tasks of the National Poisons and Pesticides Board in general and of the special measures taken on account of the mercury hazards, mainly in connection with pesticides for seed dressing in agriculture, for the preservation of wet pulp, and for slime control in the paper industry.

Presiding

Rune Lönngren, Mr., Chairman
National Poisons and Pesticides Board

Participants

Ernst Abrahamson, M.D.
former Professor and Head
National Institute of Public Health

Jörgen Backström, V.M.D.
Inspector, National Poisons and Pesticides Board

Kurt Erne, V.M. D.
Professor, National Veterinary Institute

Lars Fribera, M.D.
Professor, National Institute of Public Health

Lennart Fohrs, Agr.D.
National Seed Testing Station

Daniel Lihnell, Ph.D.
Professor, National Institute for Plant Protection

Ulla Svensén, Pharm. L.
Head of Office, National Poisons and Pesticides Board

Arne Westlin
Chief Engineer, National Workers Protection Board

- - - - - - - - - - - - - - -

Meeting with Mr. Ingemund Bengtsson, Minister of Agriculture

Appendix A (Cont'd)

Afternoon, August 30, 1971

The Wilcox Coal Institute, Department of Coal Research,
Morgantown, West Virginia

Erik Wadsworth, Ph.D.
Wilcox Coal Institute
Department of Coal Research

Glenn Ellwood, Ph.D.
University of Kentucky
Department of Earth Science

Appendix A (Cont'd)

FRIDAY
August 21, 1970

Discussions with

Lars Ehrsin, Vet. M.D.
Royal Veterinary School
Department of Clinical Chemistry

Discussions with

Östa Liljeblad
Director General of the Royal Veterinary Board
(Apelbergsg 4an 40, Stockholm)

Discussions with

Dr. Kurt Ferm
State Veterinary Medicine Institute

Appendix A (Cont'd)

Program
Conference on Toxicity of Methyl Mercury in Fish
FINLAND

Monday, August 24, 1970

0900 - The Institute of Radiochemistry
Helsinki University
Professor Jorma Miettinen
Unioninkatu 35

1330 - The Institute of Occupational Health
Dr. Pertti Suomi
Haartmaninkatu 1

Tuesday, August 25, 1970

0900 - National Board of Health
Siltavoirmankatu 16 A
Phone 718 511/-

Wednesday, August 26, 1970

0900 - National Board of Health
Siltavoirmankatu 16 A
Phone 718 511/-

APPENDIX B

TOTAL WORLD PRODUCTION OF MERCURY

1968, tons	1969, tons
9,830	10,885

TRENDS IN USES OF MERCURY IN U.S.

	1968*, tons	1969*, tons	Estimated 1974-1975†, tons
Agricultural use	130	102	101
Amalgamation	10	7	9
Catalyst manufacture	73	112	89
Dental‡	116	116	144
Electrical equipment	746	710	803
Chlor-alkali plants	663	785	869
Laboratory use†	75	78	79
Industrial controls†	302	265	351
Paints	401	370	407
Paper and pulp	16	21	9
Pharmaceuticals	16	27	25
Other uses§	302	368	226
Not accounted for¶	12	42	
	2863	3006	3172

*U.S.D.I. Bu. of Mines, MSGS 1968 & 1969 (Mercury).

†NMAB Trends in Usage of Mercury.

‡Includes redistilled mercury.

§Includes purchases for expansion and new chlor-alkali plants.

¶Mercury, chiefly from secondary recovery - uses not specified.

NOTE: These values do not include any mercury held by General Services Administration or Atomic Energy Commission.

APPENDIX B Continued

SOURCES AND EXPORT OF MERCURY IN UNITED STATES

	1968 tons	1969 tons
U.S. Domestic Mines	1097	1090
Imported	910	1164
GSA** Sales to Industry	745	117
GSA Transfers to Govt. Agencies	68	-
GSA Transfers to International Redevelopment	91	-
Redistilled*	316	380
Secondary Recovery†	402	402
GSA Stock	86	539
Exported	289	19

*This mercury is from other sources and is given additional purification.

†This mercury is recovered from battery scrap, dental amalgams and other reprocessed sources.

**General Services Administration

APPENDIX C

UNITS FOR EXPRESSING CONCENTRATIONS OF MERCURY

The different units used for expressing concentrations of mercury in various media are so diverse that confusion sometimes results. To facilitate comparisons, the following relationships are presented:

Units of Weight

1 kilogram (kg) = 1,000 grams (gm)

1 milligram (mg) = 10^{-3} gm

1 microgram (μg) = 10^{-6} gm

1 nanogram (ng) = 10^{-9} gm

1 picogram (pg) = 10^{-12} gm

Units of Concentration

A. For foods, body organs, and other solids--weight:weight basis:

1 part per million (ppm) = 1 mg/kg or 1 μg/gm

1 part per billion (ppb) = 1 μg/kg or 1 ng/gm

1 part per trillion (ppt) = 1 ng/kg or 1 pg/gm

B. For water--weight:volume basis:

1 mg/liter = approximately 1 ppm on weight:weight basis

1 μg/liter = approximately 1 ppb on weight:weight basis

1 ng/liter = approximately 0.001 ppb on weight:weight basis

C. For air--weight:volume basis:

1 μg/m^3 (cubic meter)

1 ng/m^3

REFERENCES

Ahlborg U, Berglund G, Berlin GC, et al: Cited in Berglund and Berlin, p 268

Andersson LG, Personal Communication 1970

Association of Official Agricultural Chemists: Analysis of Mercury. Official Methods of Analysis. Tenth Edition. Edited by W Horwitz. 1965, pp 375-377

Association of Official Analytical Chemists: Abstracts of 84th Annual Meeting, Oct 12-15, 1970, Washington, DC, p 10

Bäckström J: Distribution studies of mercuric pesticides in quail and some fresh-water fishes. Acta Pharmacol Toxicol 27(Suppl 3), 1969, 103 p

Bakulina AV: Effect of subacute grandsan poisoning on progeny. Sov Med 31:60-63, 1968

Berg W, Johnels A, Sjöstrand B, et al: Mercury content in feathers of Swedish birds from the past 100 years. Oikos 17:71-83, 1966

Berglund F and Berlin M: Risk of methylmercury cumulation in men and mammals and the relation between body burden of methylmercury and toxic effects, Chemical Fallout. Edited by MW Miller, GG Berg. Springfield, Charles C Thomas, 1969, pp 258-273

Berlin M and Ullberg S: Accumulation and retention of mercury in the mouse. Arch Environ Health 6:589-616, 1963

Borg K, Wanntorp H, Erne K, et al: Alkyl mercury poisoning in terrestrial Swedish wildlife. Viltrevy 6:301-377, 1969

Brandenberger H and Bader H: The determination of nanogram quantities of mercury by a flameless atomic absorption method. Helv Chim Acta 50:1409-1415, 1967

Cholak J: The nature of atmospheric pollution in a number of industrial communities. Proc Nat'l Air Pollution 2nd Symp. Pasadena, Calif, 1952

Clarkson TW: Epidemiological aspects of lead and mercury contamination of food. CFDD Symp, Ottawa, June, 1970

Deshimaru M: Cited in Nonaka I: An electron microscopical study of the experimental congenital Minamata disease in rats. Kumamoto Med J 22:27, 1969

Ellis BW and Lant SC: Elimination, tissue accumulation and cellular incorporation of mercury in rats receiving an oral dose of 203 Hg-labeled phenyl-mercuric acetate and mercuric acetate--central nervous system. Toxic Appl Pharmac 11:104-113, 1967

Eriksson E: Personal communication. Stockholm, Sweden. August, 1970

Estho H: Struggle against pests, advantages, and dangers. Proc Int Seed Testing Assoc 24:405-415, 1959

Fahmy FY: Cytogenetic analysis of the action of some fungicide mercurials. PhD Thesis, Inst Genet Univ Lund, Sweden, 1951

Falk R, Smiths JO, Ehman L, et al: Whole-body measurements on the distribution of mercury 203 in humans after oral intake of methyl radiomercury nitrate. Acta Radiologica 9:53, 1970

Fitzhugh OG, Lange EF, Nelson AA, et al: Chronic oral toxicities of mercuriphenyl and mercuric salts. Arch Ind Hyg & Occ Med 2:433-442, 1950

Fowler BL, Mohan JN, Shepard HH: The Pesticide Review. US Dept Agr, 1969, p 30

Freyschuss S and Jernelov A: Present Possibilities for Restoring Mercury Polluted Lakes. Translated report from (Sweden) Institute of Water and Air Safety, Stockholm, Feb 19, 1968

Gage JC: Distribution and excretion of methyl and phenyl mercury salts. Brit J Ind Med 27:197-202, 1970

Goldwater LJ: Occupational exposure to mercury, The Harben Lectures. J Royal Inst Public Health & Hyg, Dec 1964

Greco AR: Elective effects of some mercurial compounds on nervous system; estimation of mercury in blood and spinal fluid of animals treated with diethyl mercury and with some mercurial compounds. Riv Neurol 3:515-539, 1950

Gulf General Atomic Inc: Mercury Determinations, Activation Analysis Service, San Diego, Calif, 1969

Halldin A: Industrial sources. Mercury Symp of Nordforak Stockholm, Sweden, Oct 10-11, 1966, pp 156-159

Hannerz L: Experimental investigations on the accumulation of mercury in water organisms. Rep Inst Freshwat Res Drottningholm 48:120-176, 1968

Haq IU: Agrosan poisoning in man. Brit Med J 5335:1579-1582, 1963

Harada Y: Congenital (or fetal) Minamata disease, Minamata Disease. Study Group of Minamata Disease, Kumamoto University, Japan, 1968, pp 93-117

Hasanen E: Determination of mercury in biological material by neutron activation analysis. Suomen Kemistilehti 43:251-254, 1970

Henriksson K, Kerppinen E, Helminen M: High residue of mercury in Finnish white-tailed eagles. Ornis Fenn 43:38-45, 1966

Hinman AN: Personal communication. Oct, 1970

Hunter D, Bomford RR, and Russell DS: Poisoning by methyl mercury compounds, Quart J Med 9:193-213, 1940

Hunter D and Russell DS: Focal cerebral and cerebellar atrophy in a human subject due to organic mercury compounds. J Neur Neurosurg Psychiat 17:235-241, 1954

Irukayama K: Animal experiments with substances obtained by various treatments of the poisonous fish and shellfish, Minamata Disease. Study Group of Minamata Disease, Kumamoto University, Japan, 1968

Irukayama K, Kai F, Fujiki M, et al: Industrial wastes containing mercury compounds from Minamata factory. Kumamoto Med J 15:57-68, 1962

Irukayama K, Kondo T, Kai F, et al: Studies on the origin of the causative agent of Minamata disease, I. Organic mercury compound in the fish and shellfish from Minamata Bay. Kumamoto Med J 14:157-169, 1961

Jalili MA and Abbasi AH: Poisoning by ethyl mercury toluene sulphonanilide. Brit J Indust Med 18:303-308, 1961

Jamalainen EA: The question of seed treatment of cereals in Scandinavia. Ann Agr Fenn 7(Suppl 3):5-9, 1968

Jensen S, Personal Communication 1970

Jensen S and Jernelov A: Biological methylation of mercury in aquatic organisms. Nature 223:753-754, 1969

Jernelov A: Chemical Fallout. Edited by MW Miller, GG Berg. Springfield, Charles C Thomas, 1969, p 72

Jernelov A: Personal Communication. Stockholm, Sweden. August, 1970

Jernelov A: Laboratorieforsok rorande kvicksilvrets omvandling mellan olika forekomstformer. Vatten 5:456-458, 1968a

Jernelov A: Laboratorieforsok rorande kvicksilvrets omvandling mellan olika forekomstformer. Vatten 1:53, 1968b

Jervis RE, Debrum D, LePage W, et al: Mercury residues in Canadian foods, fish, wildlife, Trace Mercury in Environmental Materials. Summary of Progress, Canadian Health Grant Project No 605-7-510, 1970

Johnels AG: Personal communication. Stockholm, Sweden. August, 1970

Johnels AG, Olsson M and Westermark T: Esox lucius and some other organisms as indicators of mercury contamination in Swedish lakes and rivers. Bull Off Int Epiz 69:1439, 1968

Johnels AG and Westermark T: Mercury contamination of the environment in Sweden, Chemical Fallout. Edited by MW Miller, GG Berg. Springfield, Charles C Thomas, 1969, pp 221-239

Kahre L: The Swedish legislation on Hg-disinfection of spring cereal seed, procedures and experiences. Unpublished

Kanazawa J: Mercury residues in sprayed fruits, Residue Analysis of Organo-Mercuric Fungicides Sprayed on Rice and Fruits. Japan Plant Protection Association, 1965 (English summary)

Kosta L and Byrne AR: Activation analysis of mercury in biological samples at nanogram level. Talanta 16:1297-1303, 1969

Kurland LT, Faro SN, and Siedler H: Minamata disease. World Neur 1: 370-395, 1960

Kurmae A, Swensson A, Ulfvarson U, et al: Methylmercury compounds in eggs from hens after oral administration of mercury compounds. J Agr Food Chem 17:1014, 1969

Kutsuna M: Historical perspective of the study on Minamata disease, Minamata Disease. Study Group of Minamata Disease, Kumamoto University, Japan, August, 1968

Landner L: Personal communication. Stockholm, Sweden. August, 1970

Larsson JE: Environmental Mercury Research in Sweden. Swedish Environment Protection Board, Stockholm, 1970, 44 p

Lidstrom L: Surface and bond-forming properties of quartz and silicate minerals and their application in mineral processing techniques. Acta Polytechnica Scandinavica, Ch 75, Stockholm, 1968

Lidums VV and Ulfvarson U: Mercury analysis in biological material by direct combustion in oxygen and photometric determination of the mercury vapour. Acta Chem Scand 22:2150-2156, 1968

Likosky WH, Pierce PE, Hinman AH, et al: Organic mercury poisoning, New Mexico. Read at the meeting of the American Academy of Neurology, Bal Harbour, Fla, April 27-30, 1970

Lindbery CD: 55th Annual Report of the Rice Experimental Station, Crowley, La, 1964

Lindstedt G: A rapid method for the determination of mercury in urine. Analyst 95:264-271, 1970 (and personal communication, August, 1970)

Löfroth G: Methylmercury. Swedish Natural Science Research Council, Ecological Research Committee, Bull No 4, 1969, 38 p

Matsumoto H, Suzuki A, Morita C, et al: Preventive effect of penicillamine on the brain defect of fetal rat poisoned transplacentally with methyl mercury. Life Sci 6:2321-2326, 1967

Miettinen JK: Personal communication. Helsinki, Finland. August, 1970

Miettinen JK: Organic mercurials as food chain problems. Report to the FAO/IAEA Panel on the Use of Isotope and Radiation Techniques in Studies on the Fate of Pesticide Residues in the Food Chain. IAEA, Vienna, Dec 16, 1969

Miettinen JK, Tillander M, Rissanen K, et al: Distribution and excretion rate of phenyl- and methylmercury nitrate in fish, mussels, molluscs and crayfish. Proc Ninth Japan Conf on Radioisotopes, 1969, p 474-478

Miettinen JK, Blankenstein E, Rissanen K, et al: Preliminary notes on the distribution and effects of two chemical forms of methylmercury in pike. Unpublished, 1970

Miller VL, Klavano PA, and Csonka E: Absorption, distribution and excretion of phenyl mercuric acetate. Toxic and Appl Pharmacol 2:344-352, 1960

Miller VL, Klavano PA, Jerstad, AC, et al: Absorption and distribution and excretion of ethylmercuric chloride. Toxic and Appl Pharmacol 3:459-468, 1961

Mouyu S and Survanai H: Analysis of mercury residue in rice grains, Residue Analysis of Organo-Mercuric Fungicides Sprayed on Rice and Fruits, Japan Plant Protection Association, 1965 (English Summary)

Munns RK and Holland DC: Determination of mercury in fish by flameless atomic absorption: A collaborative study. In Press, Journal of the Association of Official Analytical Chemists, 1971

Norseth T: Studies on the biotransformation of methyl mercury salts in the rat. PhD Thesis, Univ Rochester, New York, 1969

Oharazawa H: Effect of ethyl mercuric phosphate in the pregnant mouse on chromosome abnormalities and fetal malformation. J Jap Obstet Gynec Soc 20:14-79, 1968

Olsson M: Discussion: Disappearance of mercury from lakes. Mercury Symp of Nordforak Stockholm, Sweden, Oct 10-11, 1968, p 179

Ordonez JV, Carrillo JA, Miranda C. M, et al: Estudio epidemiologico de una enfermedad considerada como encefalitis en la region de Los Altos de Guatemala. Bull Pan Amer Sanitary Bur 60:510-517, 1966

Ostlund K: Studies on the metabolism of methylmercury and dimethylmercury in mice. Acta Pharmacol et Toxicol 27(Suppl 1), 1969, 132 pp

Otterlind G and Lennerstedt I: Avifauna and pesticides in Sweden. Var Fagelvarld 23:363, 1964

Pekkanen : Personal communication. Helsinki, Finland. August, 1970

Perrin PA: De l'influence des vapeurs de mercure sur la secretion lactee. Zbl Biochem Biophys 13:31-73, 1911

Ramel C: Genetic effects of organic mercury compounds. Hereditas 57:445-447, 1967

Ramel C: Genetic effects of organic mercury compounds. I. Cytological investigations on allium roots. Hereditas 61:208-230, 1969

Ramel C and Magnusson J: Genetic effects of organic mercury compounds. II. Chromosome segregation in drosophila melanogaster. Hereditas 61:231-254, 1969

Rissanen K: Retention and distribution of mercury in cats. Program of the Swedish Finnish Mercury Symp, Helsinki, Nov 7, 1969, p 21-27

Rudling L: Determination of methylmercury by gas chromatography. Swedish Water and Air Pollution Research Laboratory, Stockholm, August, 1970, 4 pp

Ruzicka J and Lamm CG: Automated determination of traces of mercury in biological materials by substoichiometric radioisotope dilution. Talanta 16:157-165, 1969

Schmidt H and Harzmann R: Humanpathologische und tierexperimentelle Beobachtungen nach intoxikation mit einer organischen Quecksilberverbindung ("Fusariol") Int Arch Arbeitsmed 26:71-83, 1970

Sjostrand B: Simultaneous determination of mercury and arsenic in biological and organic materials by activation analysis. Anal Chem 36:814-819, 1964

Skerfving S: Personal communication, 1970

Skerfving S, Berlin M, Clarkson TW, et al: Maximum allowable concentrations of mercury compounds. Report of International Comm. Arch Environ Health 19:891-905, 1969

Skerfving S, Hansson K and Lindsten J: Chromosome breakage in humans exposed to methyl mercury through fish consumption. Arch Environ Health 21:133-139, 1970

Smart NA: Mercury residues in potatoes following application of a foliar spray containing phenylmercury chloride. J Sci Food Agr 15:102-108, 1964

Smart NA: Use and residues of mercury compounds in agriculture. Residue Reviews 23:1-36, 1968

Smart NA and Lloyd MK: Mercury residues in eggs, flesh and livers of hens fed on wheat treated with methyl mercury dicyandiamide. J Sci Food Agr 14:734, 1963

Stock A and Cucuel F: Die quantitative bestimmung kleinster quecksilbermengen. Naturwiss 22:390, 1934

Suzuki T, Matsumoto N, Miyama T, et al: Placental transfer of mercuric chloride, phenyl mercury acetate and methyl mercury acetate in mice. Ind Health 5:149-155, 1967

Svensfor Fotlninass Sampling, NR 387, Environmental Franchise Board, 1969

Takeuchi T: Pathology of Minamata disease, Minamata Disease. Study Group of Minamata Disease, Kumamoto University, Japan, August, 1968, pp 141-252

Takeuchi T: Biological reactions and pathological changes of human beings and animals under the condition of organic mercury contamination. International Conference on Environmental Mercury Contamination, Ann Arbor, Michigan, October, 1970, 30 p

Tammisto ES, Koljonen K and Santaoja I: The effects of seed disinfectants containing alkoxy alkyl mercury derivations on the mercury content of hen's eggs in feed test with disinfected cereals. Ann Agr Fenn 7(Suppl 1):15-21, 1968

Tejning S: Biological effects of methyl mercury dicyandiamide-treated grain in the domestic fowl Gallus gallus L. Oikos Suppl 8, 1-116, 1967a

Tejning S: Mercury in pheasants (Phasianus colchicus L.) deriving from seed grain dressed with methyl and ethyl mercury compounds. Oikos 18.334-344, 1967b

Tejning S: Mercury content in the blood system, blood plasma and in heavy fish eaters from different regions and the connections between mercury content in fish together with a proposal on international food hygienic limits on mercury applicable to fish and fish products. Report 670731, Clinic of Occupational Medicine, Univ Hosp, Lund, Sweden, 1967c

Tejning S: No fish for mother. Scandinavian Times 4:24-25, 1970a

Tejning S: Personal communication. Stockholm, Sweden. August, 1970b

Tejning S and Vesterberg R: Alkyl mercury treated seed in food grain. Poultry Sci 43:6-11, 1964

Tillander M, Miettinen JK and Koivisto I: Excretion rate of methyl mercury in the seal (Pusa hispida). Presented at FAO Technical Conf on Marine Pollution and Its Effect on Living Resources and Fishing, Rome, Dec 1970

Tillander M, Miettinen JK, Rissanen K, et al: Discussion: Excretion of phenyl and methyl mercury nitrate after oral administration or intramuscular injection in fish, mussel, mollusc and crayfish. Mercury Symp of Nordforsk Stockholm, Sweden, Oct 10-11, 1968, p 181-183

Tonomura K and Kanzaki F: The reductive decomposition of organic mercurials by all-free extract of a mercury resistant pseudomonas. Biochem Biophys Acta 184:227-229, 1969

Tonomura K, Maeda K, Futai F, et al: Stimulative vaporization of phenylmercuric acetate by mercury-resistant bacteria. Nature 217:644-646, 1968

Tsubaki T, Sato T, Kondo K, et al: Outbreak of intoxication by organic mercury compound in Niigata Prefecture. Japan J Med 6:132-133, 1967

Uchida M, Makio , Hirakama K, et al: Biochemical studies on Minamata disease III. Relationships between the causal agent of the disease and the mercury compound in the shellfish with reference to their chemical behaviors, Kumamoto Med J 14:171-179, 1961a

Uchida M, Hirakawa K, and Indue T: Biochemical studies on Minamata disease IV. Isolation and chemical identification of the mercury compound in the toxic shellfish with special reference to the causal agent of the disease. Kumamoto Med J 14:181-187, 1961b

Ulfvarson U: Distribution and excretion of some mercury compounds after long term exposure. Internat Arch F Gewerbepath U Gewerbehyg 19:412-422, 1962

Ulfvarson U: The effect of the size of the dose on the distribution and excretion of mercury in rats of the single intravenous injection of various mercury compounds. Toxicol Appl Pharmacol 15:517-524, 1969

Wenninger JA: Direct microdetermination of mercury in color additives by the photometric mercury vapor procedure. J Assoc Offic Anal Chem 48:826-832, 1965

Werner J: Analytiska aspekter pa utslapp till vattendrag av metalliskt och oorganiskt kvicksilver. IVL Mimeographed Publ. B 20, June, 1967

Westermark T and Sjostrand B: Activation analy is of mercury. Int J Appl Radiat Isotopes 9:1-15, 1960

Westöö G: Determination of methylmercury compounds in foodstuffs. I. Methylmercury compounds in fish, identification and determination. Acta Chem Scand 20:2131-2137, 1966

Westöö G: Determination of methylmercury compounds in foodstuffs. II. Determination of methylmercury in fish, egg, meat and liver. Acta Chem Scand 21:1790-1800, 1967

Westöö G: Determination of methylmercury salts in various kinds of biological material. Acta Chem Scand 22:2277-2280, 1968

Westöö G: Mercury and methylmercury levels in some animal foodproducts. Vars Foda 7:137-154, 1969

"
Westöö G: Personal Communication, 1970

"
Westöö G and Rydalv M: Mercury and methylmercury in fish and crayfish. Vars Foda 3:19-111, 1969

Williston SH: Mercury in the atmosphere J Geophysical Res 73:7051-7055, 1968

Wishart W: A mercury problem in Alberta's game birds. Alberta 13:4-9, 1970

Wood JM, Kennedy FS and Rosen CG: Synthesis of methyl mercury compounds by extracts of a methanogenic bacterium. Nature 220:173-174, 1968